

APPENDIX I

Background Water Quality Assessment

In order to evaluate the impact of Kennecott's mining operations on the surrounding groundwaters, the background water quality needs to be defined. Much of the information presented in this section was provided by Intera Technologies Inc.

Due to the complex number of variables that have and still are impacting groundwaters in the area (i.e. the ore body, surface waters, historic leach water discharges, distinct geologic zones and flushing of mineralized zones, reservoir and evaporation pond seepage), establishing background water quality is extremely difficult. In fact, the water quality data indicate that the background water quality for the groundwaters in the western and southern part of the study area is much poorer than that to the north or to the east.

A groundwater contaminant transport flow model will not be completed for this study, although the U.S.G.S. will be completing a groundwater flow model. A contaminant transport flow model is not required since the critical contaminants are SO_4 and TDS, and the geochemical controls on these constituents are negligible as compared to the flow controls. The results of the U.S.G.S. model should, however, be very useful in defining the extent and rate of groundwater contaminant flow movement from specific source areas.

Groundwaters in the study area typically reflect inputs from the following sources:

- (1) Salts and other solids precipitated with rain or snow. Although the absolute concentrations of dissolved solids in precipitation are low, near surface evaporation and transpiration can lead to significant increases in these concentrations. In urban areas such as Salt Lake City, the concentrations of dissolved salts in infiltrating waters are often higher than natural levels. In addition, the relative concentrations of salts may be quite distinct from precipitation in non-urban areas. For example, the concentrations of sodium and chloride ions may be elevated due to the application of salt on roadways.
- (2) Weathering or dissolution of rock masses. As water from precipitation infiltrates into solid rock (e.g., a mountain range) chemical reactions take place which alter the chemistry of the water. These reactions generally lead to an increase in the dissolved solids content of the infiltrating waters because these waters are commonly undersaturated with respect to the mineralogic constituents of the rocks. In addition, these reactions can substantially modify the pH and oxidation potential of the waters.
- (3) Reactions between sediments and groundwaters. Although sediments are ultimately derived from crystalline rocks, participation in the sedimentary cycle results in a homogenization of components from different sources. In addition, minerals precipitated from surface waters may be interbedded with detrital sediments (e.g., sand and clay). This leads to chemical compositions that are not found among the crystalline rocks which in turn leads to distinct groundwater compositions. Detrital sediments also have much greater surface area

per unit volume than crystalline rocks. This provides more reaction potential for the waters in the pore spaces of these sediments.

- (4) Connate waters. Connate waters are waters that were trapped within sediments or other rock types during burial. They often have high dissolved solid concentrations in part as a result of prolonged reaction with the enclosing host rocks. In the case of the Salt Lake Basin, brines and related minerals from earlier stages of the Great Salt Lake or its precursors may locally be trapped within the sediments filling the basin.
- (5) Geothermal waters. Geothermal waters are waters that have been heated at depth and transported upward. These waters can mix with cooler waters in the shallower aquifers. They generally have a distinctive geochemical signature including high silica, arsenic, chloride, and low sulfate and carbonate contents.
- (6) Irrigation. Water used in irrigation may acquire various distinctive components as a result of agricultural activities. Because irrigation is more common on the east side of the Jordan Valley, the impact of irrigation on groundwater geochemistry should be more evident there.
- (7) Canal overflow and seepage. Several canals that carry water from Utah Lake and other sources to the south traverse the Jordan Valley from south to north. These canals are generally unlined and commonly leak water to the subsurface.
- (8) Mining operations. The extraction and processing of sulfide ores results in the production of waters with elevated metal and sulfate concentrations.

The large range in absolute concentrations of various components observed in the present-day natural waters makes it impossible to establish a single background or natural water composition against which all present day waters in the Salt Lake Basin can be evaluated for evidence of contamination. In order to evaluate the relative impact of mining operations at the Bingham Canyon Mine on groundwater quality in the southern Salt Lake Basin, the range of concentrations that might be expected from other sources needs to be documented. In the following, ranges for the ionic constituents in waters from inputs one through seven will be discussed.

- (1) Precipitation. The chloride concentrations measured in precipitation at 3 different sites in Salt Lake County, as reported by Hely, et al. (1971) are shown in Figure I-1. The concentrations are commonly low (less than 8 mg/l), but vary considerably depending on such factors as the amount of precipitation, the location of the precipitation relative to sources of particulates, as well as other factors. The concentrations of major ionic constituents in snow collected from mountains in Utah in 1959 are listed in Table I-1. The relatively high sulfate to chloride ratios (see below) in precipitation in the Utah area are noteworthy.

- (2) Weathering and dissolution of rock masses. Waters that have infiltrated mountainous areas and have reacted with the rock masses in these mountains are locally emitted at springs in the high mountains and along mountain fronts. These waters also enter the alluvial aquifers in the subsurface. Analyses of spring waters are shown in Table I-2. There is great variability in the composition of spring waters from the Salt Lake Basin, although there appears to be some correlation between composition and elevation of the collection point. That is, high mountain springs have the lowest dissolved solids content but the highest sulfate to chloride ratios while the springs emitted near the mountain fronts have the highest dissolved solid contents and the lowest sulfate to chloride ratios. This trend likely reflects progressive modification of infiltrating precipitation through reaction with the host rocks and mixing with in-situ waters in the cores of the ranges. Springs emitted at the mountain fronts may also contain contributions from deep waters brought up along high angle normal faults bounding the ranges. These waters are commonly high in chloride concentrations and have low sulfate to chloride ratios. Further, they occasionally have elevated concentrations of components such as arsenic and silica which suggest an association with geothermal sources (see below). The water from Barney's Spring north of the Bingham area may represent this type of water. Similar waters are found along range fronts on the east side of the Jordan Valley (Spencer, 1983; Table I-4).
- (3) Reactions between sediments and groundwaters. The amount of solute added to or extracted from groundwater as a result of reaction with the aquifer matrix materials depends on the residence time of the waters and the composition of the matrix. Recharge to the aquifers of the south-eastern Jordan Valley is predominantly derived from the Wasatch Range (Waddell et al., 1986). This recharge infiltrates rapidly with the result that much of the groundwater in the east side of the Jordan Valley has a relatively low total dissolved solid content (Figure I-2) and sulfate to chloride ratios similar to precipitation. On the west side of the valley, there is less recharge and the aquifer matrix materials are likely more reactive (i.e., carbonates and volcanics) resulting in groundwaters with higher dissolved solids contents and generally lower sulfate to chloride ratios (Figure I-2). Water from wells in the south-central Jordan Valley commonly have elevated silica concentrations, well above saturation with quartz, cristobalite, and in some cases even amorphous silica. This may reflect the volcanic provenance (i.e., derivation) of the aquifer matrix materials in this area although a geothermal contribution cannot be ruled out. If there are salts interbedded with the sediments (e.g., from the Great Salt Lake or its precursors), these should be more evident in waters from the west side because the higher recharge rate on the east side would flush the salts out more rapidly. Sample W-336 (Table I-3) from the west side of the valley may reflect such input.
- (4) Connate waters. Although connate waters are likely uncommon in sediments of the Jordan Valley, they may be present locally and occasionally intercepted by a drill hole or well (i.e. W360). These waters would be of limited volume and therefore show up mainly in the

early stages of pumping of a given well or in a specific zone. This may be reflected in the trend of water compositions from well W-360 (see Kennecott annual reports) from the west side of the valley. Alternatively, this well could have penetrated a salt-bearing layer or contain a geothermal water component.

- (5) Geothermal waters. Waters from Well W-340 have temperatures of 60-80 degrees Centigrade that are well above the average temperature of the other wells (approximately 15 degrees Centigrade) in the southern Jordan Valley. The composition of the waters from this well clearly reflect a geothermal source as indicated by the high concentrations of SiO₂, Cl, F, K, Na (Table I-3) and by elevated concentrations of As, Ba, and Mn. Although a number of other wells in the southern Jordan Valley have elevated SiO₂ concentrations suggestive of a geothermal association, they do not show all the other chemical attributes of geothermal waters. Note that the geothermal waters do not have elevated concentrations of Se.
- (6) Irrigation activities. According to Waddell et al. (1986), much of the irrigated land in the Jordan Valley south of Kearns occurs east of the Jordan River. This suggests the effects of irrigation on groundwater quality should be most evident in wells on the east side of the valley, particularly those completed in the shallow unconfined aquifer. The data shown in Figure I-2 indicate that waters from wells on the east side of the Jordan Valley south of Murray generally have sulfate to chloride ratios less than 2.5. If the waters below Little Cottonwood Creek are excluded from the data set, the ratios are less than one for both the shallow and deep aquifers. This suggests agricultural activities do not contribute contaminants that have high sulfate to chloride ratios to the groundwater system. However, agriculture may contribute arsenic, nitrates, and organic compounds to the regional groundwater system. Detectable levels of arsenic are found in the Jordan River and in water from springs in the shallow unconfined aquifer along the east and west banks of the Jordan River. These elevated arsenic levels may represent the seepage of irrigation waters from the shallow unconfined aquifer along the river banks. Alternatively, they may represent geothermal input further upstream.
- (7) Canal overflow and seepage. According to Waddell et al. (1986), canal seepage could represent as much as 13 percent of recharge in the Jordan Valley. The chemistry of the canal waters is similar to that of the Jordan River because all of these waters originate from Utah Lake south of the Jordan Valley.

Mining operations are known to be a major source of sulfate. However, they add relatively little chloride to the groundwater system, and the ratio of sulfate to chloride concentrations can probably be used to distinguish inputs from mining operations from other inputs in the southern Jordan Valley. Both sulfate and chloride ions behave as conservative components in most of the groundwaters of the southern Jordan Valley. The exceptions are waters with high sulfate contents just downgradient from the reservoirs and possibly those immediately downgradient of the evaporation ponds. These waters are considered separately.

Sulfate to chloride ratios for various waters from the southern Jordan Valley are plotted against chloride concentrations in Figure I-3a. Most of the waters outside the Bingham area have ratios that are less than or equal to 1.0. Young recharge (i.e., recent precipitation and spring waters) has higher ratios but low chloride concentrations. These waters reflect anthropogenic input of sulfate to the drainage basin on a regional scale (Figure I-3b). Much of the compositional variation in the waters plotted in Figure I-3a can be explained as a mixture of young recharge and a high chloride component from either geothermal waters, salty connate waters, dissolved evaporates, or infiltrated road salt. A third component in Figure I-3a is represented by waters from deep wells such as W-31 and W-32. These waters show no evidence of near surface sulfate contamination and may represent prehistoric values for the basin (Figure I-3b).

The impact of the ore body at Bingham on groundwater quality in the southern Salt Lake Basin prior to the commencement of mining activities cannot be easily evaluated with the available historic analytical data. This impact, however, was estimated by Intera through calculations. In the calculations, waters from well W-31, a well with low total dissolved solids from just north of the Bingham area, were reacted with ores composed of the Cu, Fe, Pb, and Zn sulfides (i.e., chalcopyrite, pyrite, galena, and sphalerite). Typical results are shown in Table I-4. The primary control on the amount of sulfide that is dissolved into the groundwater is the oxidizing capacity of the solution. In the calculations, the water was assumed to contain 10 mg/l oxygen, an average value for precipitation. If the groundwater and the sulfides are treated as a closed system, very little reaction takes place.

MODIFICATIONS TO BACKGROUND WATER CHEMISTRY RESULTING FROM MINING

A primary objective of the present study is to distinguish the impact of mining operations at Bingham Canyon from the impacts of other possible contaminant sources on the quality of groundwaters in the southern Salt Lake Basin. This objective has been addressed in two ways: (1) through the use of ratios of conservative components and (2) by the distribution of key elements such as Se that have very low natural concentrations but are enriched in the mined ore.

Sulfate to chloride ratios and chloride concentrations of waters from the Bingham Mine area, the Jordan River, and the town of South Jordan, have been plotted in Figure I-4. The reservoirs and evaporation ponds associated with the mine have sulfate to chloride ratios that plot off of the diagram, although they have normal chloride contents. This implies they can contribute substantial amounts of sulfate but little additional chloride to the groundwater system as noted previously. Waters from many of the wells downgradient from the reservoirs, evaporation ponds, and tailings reflect the influence of mining inputs. Data from a few wells have been plotted. These wells (P-190A, K-109, K-60, and P-197A) are located between the main reservoir and the evaporation ponds and are fairly representative of the high SO_4 to Cl ratio. By contrast, the SO_4 to Cl ratios in waters from the Great Salt Lake are low (0.07 - 0.19).

Wells located in and around South Jordan reflect a more complicated regime likely involving the mixing of waters from different sources. The trends

of analyses for waters from wells W-301, W-302 and W-306 suggest they represent mixtures of mining related waters with high sulfate to chloride ratios and low chloride concentrations, as well as high chloride waters with low sulfate to chloride ratios (such as waters contaminated with road salt or high chloride connate waters). Analyses of waters from wells W-304 and W-305 suggest these waters contain an additional component which may be Jordan River water or deep uncontaminated waters.

A generalized plan view of sulfate to chloride ratios in the southwestern Jordan Valley is shown in Figure I-5. Major sulfate contamination occurs in the Bingham Pit and waters downgradient from the reservoirs, the evaporation ponds, and the southern dumps. Areas along the lower reaches of Bingham, Midas, and Butterfield Creeks, show lesser amounts of sulfate contamination. A band of relatively pristine water traverses the center of the area and separates the reservoir plume from the plumes originating from the evaporation ponds and the southern dumps. This band may represent older waters that have not been contaminated or more likely young infiltration which follows zones of high conductivity that lie outside of the aquifer volumes influenced by the sources of contamination.

A plot of selenium concentrations in surface and well samples from the southwestern Jordan Valley is shown in Figure I-6. Most waters in the area have selenium concentrations that are below the limit of detection (0.004 mg/l). Detectable selenium concentrations are found in surface samples from the Bingham pit, Bingham Canyon, the reservoirs and evaporation ponds. Groundwaters with detectable selenium concentrations are located just downstream of the reservoirs, in South Jordan and along the Midas Creek drainage. These distributions are generally consistent with the SO_4/Cl ratio plot shown in Figure I-5.

Figure I-7 shows a cross-section through the reservoir and the evaporation ponds. The perforation depths in wells within one-half mile to the north or south of the cross-section are shown along with the static water levels and the ranges in sulfate concentrations of water samples obtained from the wells over a 5 year period. The sulfate data suggest there are separate plumes originating at the reservoir and the evaporation ponds. The reservoir plume is limited vertically to a depth of less than 450 feet, as shown by a 1300 foot drill hole geophysical log (P-277) completed along Bingham Creek within the plume boundary. The plume originating beneath the evaporation ponds appears also to be limited to the shallow unconfined aquifer.

The sulfate concentrations in waters from wells along the transect shown in Figure I-7 have been plotted on a log concentration versus distance plot in Figure I-8. Several important features of the contaminant plumes are evident in this plot. The sulfate concentrations in wells within a mile east of the reservoir are high, indicating there has been very little retardation of sulfate over this distance. Between wells P-213B and K-106 (approximately 1000 feet), the sulfate concentration drops by a factor of 15. This decrease cannot be attributed solely to dispersion or dilution, although increased dilution from seepage of good quality waters from the cemetery pond probably impacted the groundwaters. As discussed in the following section, precipitation of a sulfate bearing phase (e.g. gypsum) is a more likely explanation. Waters in the shallow wells east of K-106 and east of the evaporation ponds have sulfate levels that are consistently

high. This reflects the fact that these waters are not over-saturated with any sulfate-bearing phase and that there is only limited dispersion of the sulfate contaminant. The low sulfate concentrations in waters from wells W-189, P-192B, P-194A and B, P-207B, and P2-40B suggest that although these wells are downgradient from Kennecott facilities, these waters are not contaminated with sulfate derived from mining operations.

Log concentrations versus distance plots for most of the other components for which data are available are presented in Appendix I-A. A brief discussion of these diagrams is presented here.

The chloride plot emphasizes the limited variation in chloride along the transect. In general, chloride concentrations are low but tend to decrease slightly with distance from the reservoirs presumably as a result of dispersion and dilution. Wells around South Jordan (W-300, W-304) have unusually high chloride contents. As noted earlier this may reflect the infiltration of waters contaminated with road salt or simply the existence of a high chloride source (e.g., salty connate waters, dissolution of interbedded salt, etc.) beneath South Jordan.

The variations in pH, HCO_3 and Ca are interdependent. Acid waters (pH 3-4) from the mining operations infiltrate beneath the reservoirs and evaporation ponds and react with the aquifer materials, especially limestone fragments. This reaction decreases the hydrogen ion concentrations (i.e., increases pH) and releases CO_2 , HCO_3^- , Ca^{++} and Mg^{++} . These relations are evident in the diagrams for pH, HCO_3 , and Ca in Appendix I-A. The variations in Ca are further complicated by precipitation reactions (e.g., gypsum) and dilution. Note that Mg has not been plotted due to a lack of sufficient data.

The variation in sodium (Na) concentration is limited because this element is largely retained in the aqueous phase, much like chloride.

Plots of the metals Al, Fe, Mn, Cr, Ni, Cu, Zn, Cd, and Pb show drastic decreases in concentration as the waters are neutralized in the subsurface. These decreases reflect precipitation reactions combined with sorption of metals on newly formed precipitates.

The variations in arsenic (As) and selenium (Se) largely reflect coprecipitation with sulfate, and dispersion and dilution.

Silica (SiO_2) variations suggest the concentration of this component is controlled by coexistence with chalcedony, a form of quartz.

GEOCHEMICAL MODELING

The cross-sections shown in Figures I-7, I-8, and those in Appendix I-A indicate that the concentrations of Al, As, Cd, Cr, Cu, Fe, Mn, Ni, Pb, and Zn decrease to near background levels within 1 to 2 miles downgradient from the reservoirs and the evaporation ponds while the concentrations of SO_4 and Se decrease by a factor of 50 or more. Within the same distance, the pH and concentrations of Ca, K and HCO_3 increase to near background levels while the concentrations of Na, F, and Cl show no simple trends but remain close to background levels. These observations indicate most of the metals

are being strongly retarded during transport through the unconfined aquifers downgradient from the reservoir and the evaporation ponds. In addition, they reflect the results of reaction between the aquifer matrix and the infiltrating acid mine waters.

The matrix of the unconfined aquifer below the reservoir undoubtedly contains limestone fragments that have been eroded from the dominantly carbonate quartzite bedrock of the Oquirrh Mountains. As the acid (pH 2.5-4.1) reservoir waters infiltrate into this aquifer, they would be neutralized by the carbonate in the limestone fragments. With neutralization, the solubility products of various mineral species containing the metals listed above would be exceeded causing the metals to be precipitated.

The geochemical reaction code PHREEQE has been used by Intera Technologies Inc. to model these precipitation reactions. First, the composition of a water sample from well K-26 (pH = 3.1) was reacted with calcite at a constant $P_{CO_2} = 10^{-2}$ and a $pE = 8.0$. The K-26 water was chosen because it is typical of waters infiltrating from the reservoir and data for all the constituents were available in the three Annual Kennecott Mine Groundwater reports. The solution resulting from the neutralization reaction had a pH of 6.8 and was supersaturated with approximately a dozen minerals containing the metals listed above. This solution was allowed to equilibrate with these minerals resulting in their precipitation in the amounts listed in Table I-5. The composition of the solution remaining after precipitation of the minerals is also shown in Table I-5. Basically, precipitation removed most of the Al, Cu, and Fe from the solution and increased the pH to 7.1. Varying amounts of Ag, Cd, Mg, Mn, Pb, Zn, SiO_2 , and SO_4 were also precipitated (Table I-5). At the same time, the concentrations of Ca and HCO_3^- were increased as a result of calcite dissolution. The concentrations of As, K, Na, Ni and Cl remained unchanged because they were not included in any of the phases precipitated.

Although the solution composition resulting from the precipitation step is much closer to background values than the original solution (Table I-5), the concentrations of many of the metals and of sulfate remain high. Some reductions in these concentrations can be expected from the solid solution of the trace metals in other phases. Sorption on the surfaces of minerals will also reduce the concentrations of metals in solution (e.g., Ni on goethite). Unfortunately, we cannot model the sorption reactions in a quantitative fashion at the present time.

Another possible mechanism for retardation of As, Cd, Pb, Zn and presumably some of the other metals, is through precipitation as sulfide minerals. As water infiltrates into an aquifer, its oxidation potential is no longer buffered directly by the atmosphere. If there are materials in the aquifer (e.g., bacteria, organics, etc.) capable of reducing the oxidation potential of the water, sulfides may become stable phases. In the case of the Bingham area, several wells (K-120, P-190A, P-192B, P-193A, P-194A and B) downgradient from the reservoir but upgradient from the evaporation ponds contain detectable sulfide (S) concentrations suggesting waters in these wells are more reduced than the wells further upgradient.

To assess the effect of reducing conditions on the transport of the metals, calculations were carried out at a lower oxidation potential ($pE = -2.0$). The "final" solution in Table I-5 was used as a starting composition. The calculations indicate sulfides of Cu, Cd, and Pb would be precipitated along with metallic silver (Table I-6). Although an oxidation potential of $pE = -2.0$ may not represent a true value for the aquifer, the calculation does indicate these metals can be fixed in the aquifer under reducing conditions. Ideally, the oxidation potential of the aquifer would be known at numerous points along the flow path from the reservoir. Unfortunately, reliable values for this parameter would be very difficult to obtain although this problem can be alleviated to some degree through mineralogical analysis of core samples from the aquifer. If the actual minerals containing the metals at various points along the flow path could be identified, the oxidation potential of the solutions from which these metals were precipitated could be calculated. These could in turn be used to further define and constrain the modeling calculations.

If as the modeling suggests, the metals are precipitated from the acid reservoir solutions within a short distance from the points where these solutions enter the aquifer, this will result in the fixation of high metal concentrations in the aquifer over time. It would be reasonable to ask how quickly these metals would redissolve and be transported if the input solution was changed. For example, if the mine ceased to operate and the composition of the recharge reverted to "background" values, at what rates would the metals be transported downgradient through the aquifer? This question was addressed by allowing a background water composition (W-31) with 10 mg of O_2 to equilibrate with the mineral assemblage listed in Table I-5. The results of this calculation are presented in Table I-7.

The calculated concentration of most of the metals are near background levels. Relative to water from well P-197B, elevated levels are calculated for Ag, Mg, Mn, Pb, and SO_4 . If the oxidation potential of the solution had been set to reflect reducing conditions, the concentrations of Ag, and Pb would have been below background levels. The calculated concentrations of Mg, Mn, and SO_4 are above background levels and could present a problem. However, the calculations assumed equilibrium conditions which allow the maximum amount of a dissolving mineral to enter the solution. If the dissolution kinetics for these phases are slow relative to the water flow velocity, the concentrations observed in solution would be smaller. Data on the appropriate dissolution kinetics are not currently available.

SUMMARY

Waters in the southern Salt Lake Basin contain contributions from many sources, including precipitation, weathering reactions, sediment-water interactions, connate or formation waters, geothermal waters, agricultural activities, canal overflow and seepage, and mining and other industrial operations. The mining operations are reflected in high ratios of sulfate to chloride concentrations and elevated concentrations of elements such as Se in waters in the southwestern part of the basin.

The principal impact areas of the Bingham Mine on groundwater quality in the Salt Lake Basin include the area bounded by the Bingham and Butterfield Creek drainages on the north and south and the Jordan River to the east.

Plumes of contaminated water are evident in the aquifers downstream from the reservoirs, evaporation ponds, and the southern dumps. Less contaminated waters occur in the remaining area. The plume originating from the reservoirs extends between one and two miles downstream in the upper aquifer. The plume originating from the evaporation ponds appears to be limited to the shallow unconfined aquifer. The plume originating from the southern dumps has not been investigated.

The restricted volume of the reservoir plume, given the long period of time over which the mine has been in operation and the relatively large hydraulic conductivities of the aquifers, suggests the contaminants are being retarded. The acidic nature of the infiltrating reservoir waters suggest that they react strongly with carbonate components presumed to be present in the aquifer matrix.

Preliminary geochemical modeling of the acid neutralizing reactions and consequent precipitation reactions involving most of the contaminant components provides a reasonable first approximation to an explanation for the retardation. A requirement of the modeling calculations is that the oxidation potential of the waters decrease with transport through the first few miles of aquifer downstream from the reservoirs. Some evidence for this decrease is found in the presence of reduced sulfur in wells at this distance from the reservoirs.

Chemical reactions that might occur in the plume originating from the evaporation ponds have not been modeled specifically but would likely be similar to those postulated for the reservoir plume.

The long term effects of contaminant transport have not been fully evaluated. However, due to the fact that the metals are precipitated from the infiltrating mine waters within short distances from where they enter the aquifer, metal contamination of the aquifer is not the critical concern. Increased levels of sulfate, and possibly arsenic and selenium are of concern because these components are transported with groundwater to a greater degree (i.e., they are less attenuated). Consequently, further modeling will concentrate on refining the hydrogeologic flow regime in order to define the existing and future lateral and vertical extent of the sulfate and selenium plumes both on site and off site.

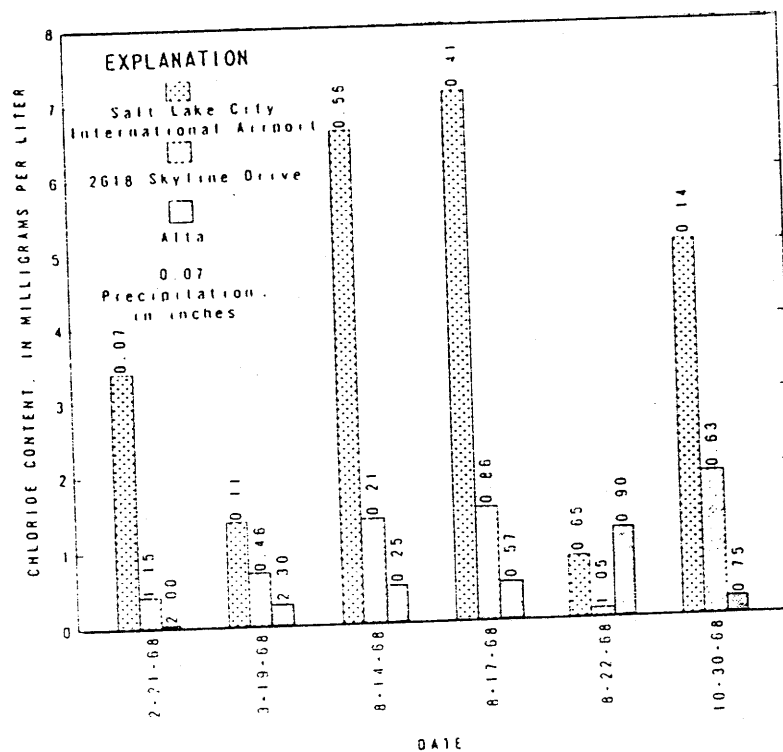
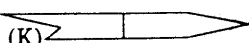
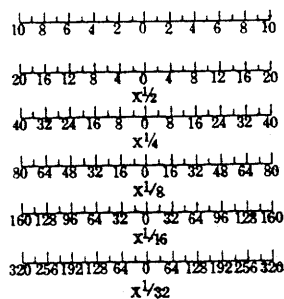


Figure I-1. —Chloride content of precipitation at three sites in Salt Lake County.

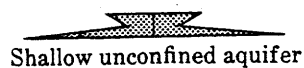
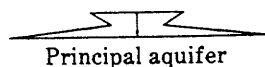
Ref: Hely et al.; (1971)

EXPLANATION

Calcium (Ca) Magnesium (Mg) Sodium (Na) + Potassium (K)		Bicarbonate (HCO_3) Sulfate (SO_4) Chloride (Cl)
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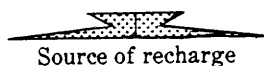
AQUIFER




•²

Wells at which chemical quality data were obtained
Number indicates number of wells at site

SURFACE WATER



▼
Surface - water sampling site


Approximate boundary of valley fill

Hydrology by C. A. Harr (1970)

Figure 2 Legend

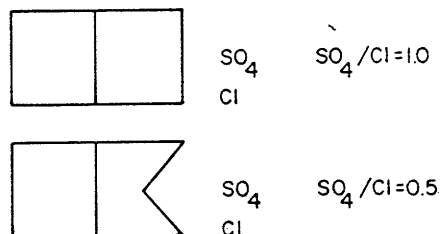


Figure I-2. (Legend)

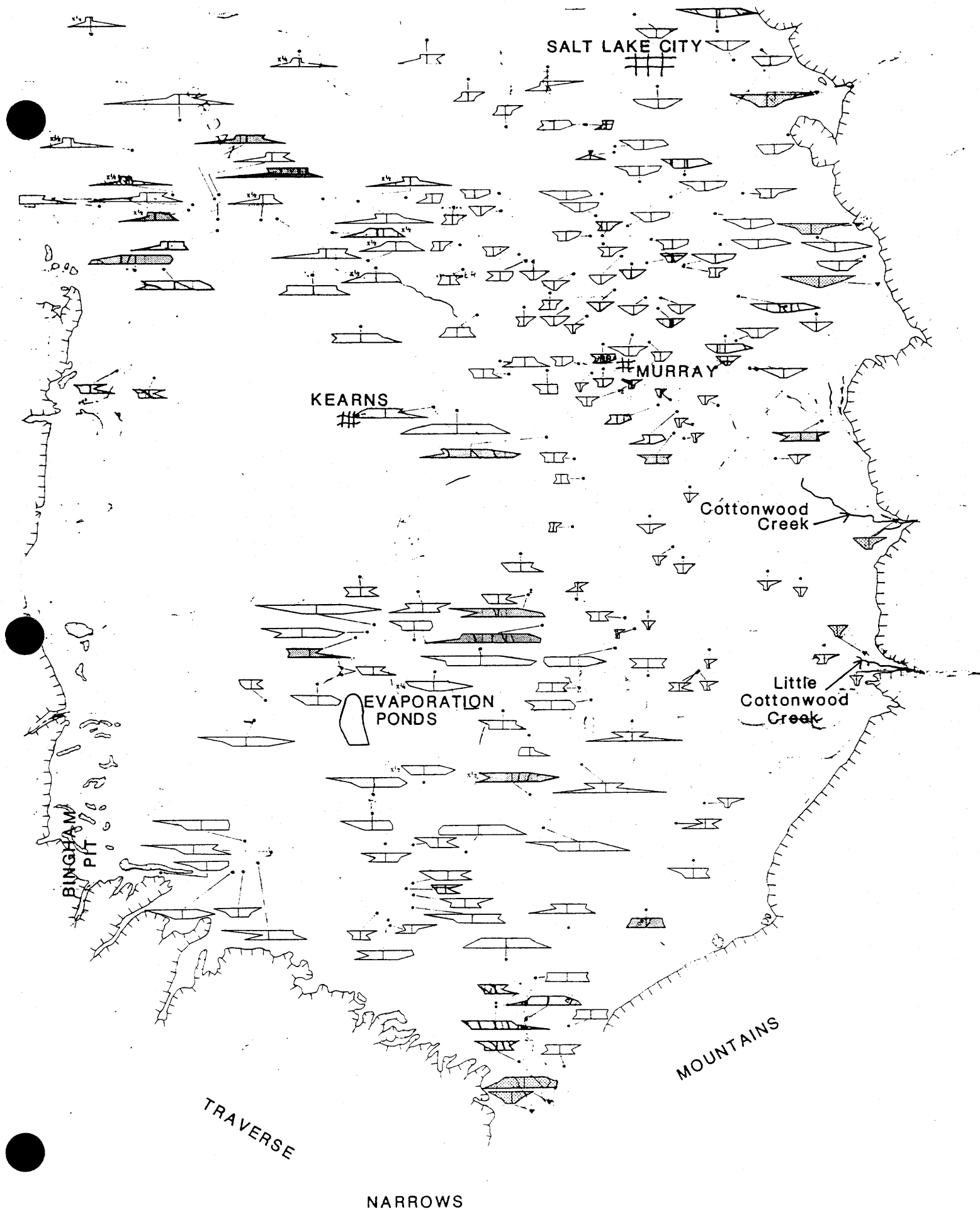


Figure I-2. Water Quality Map

BACKGROUND $\text{SO}_4^{2-}/\text{Cl}^-$

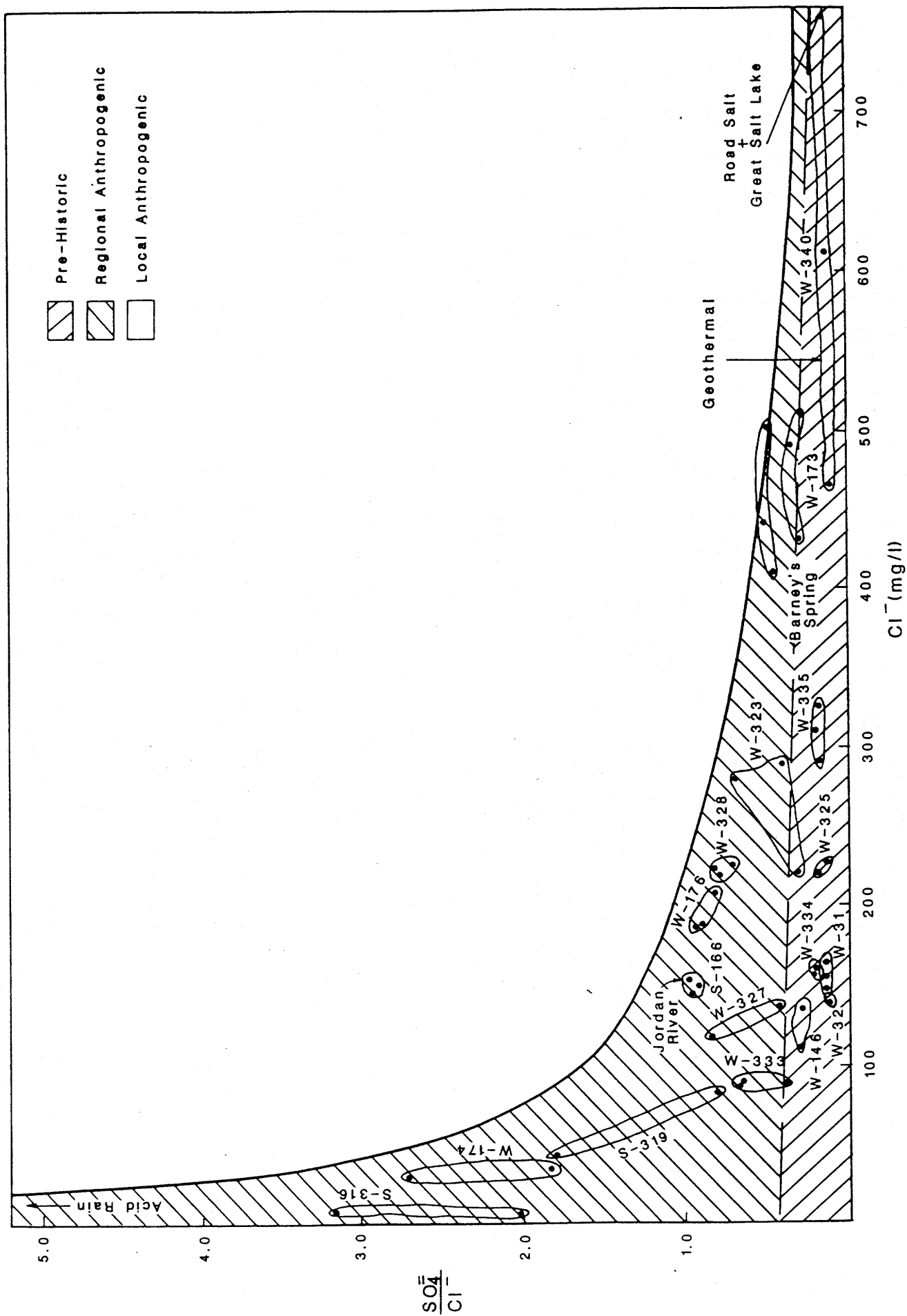


Figure I-3. SO_4 To Cl Ratio

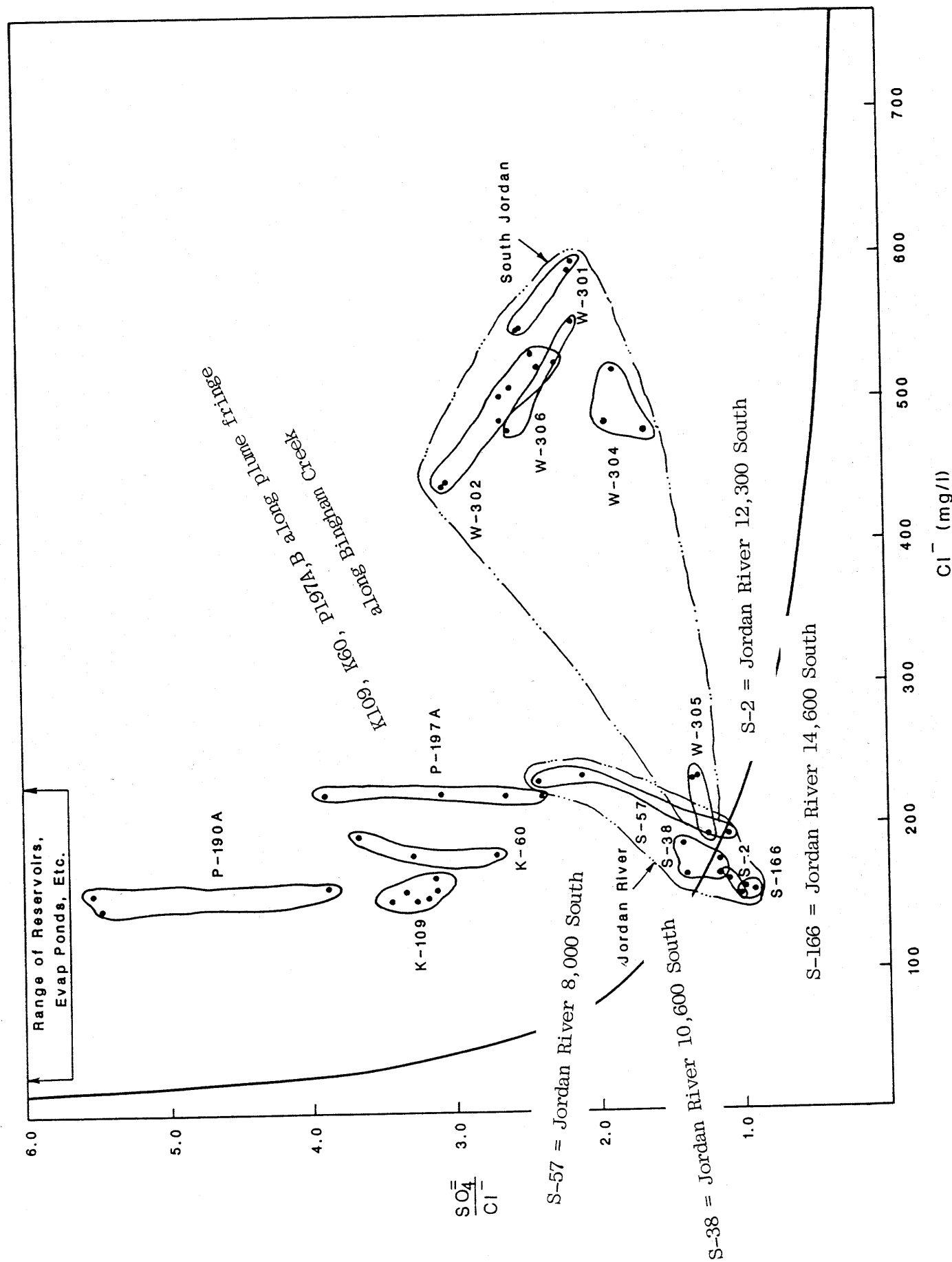


Figure I-4. SO_4 To Cl Ratio

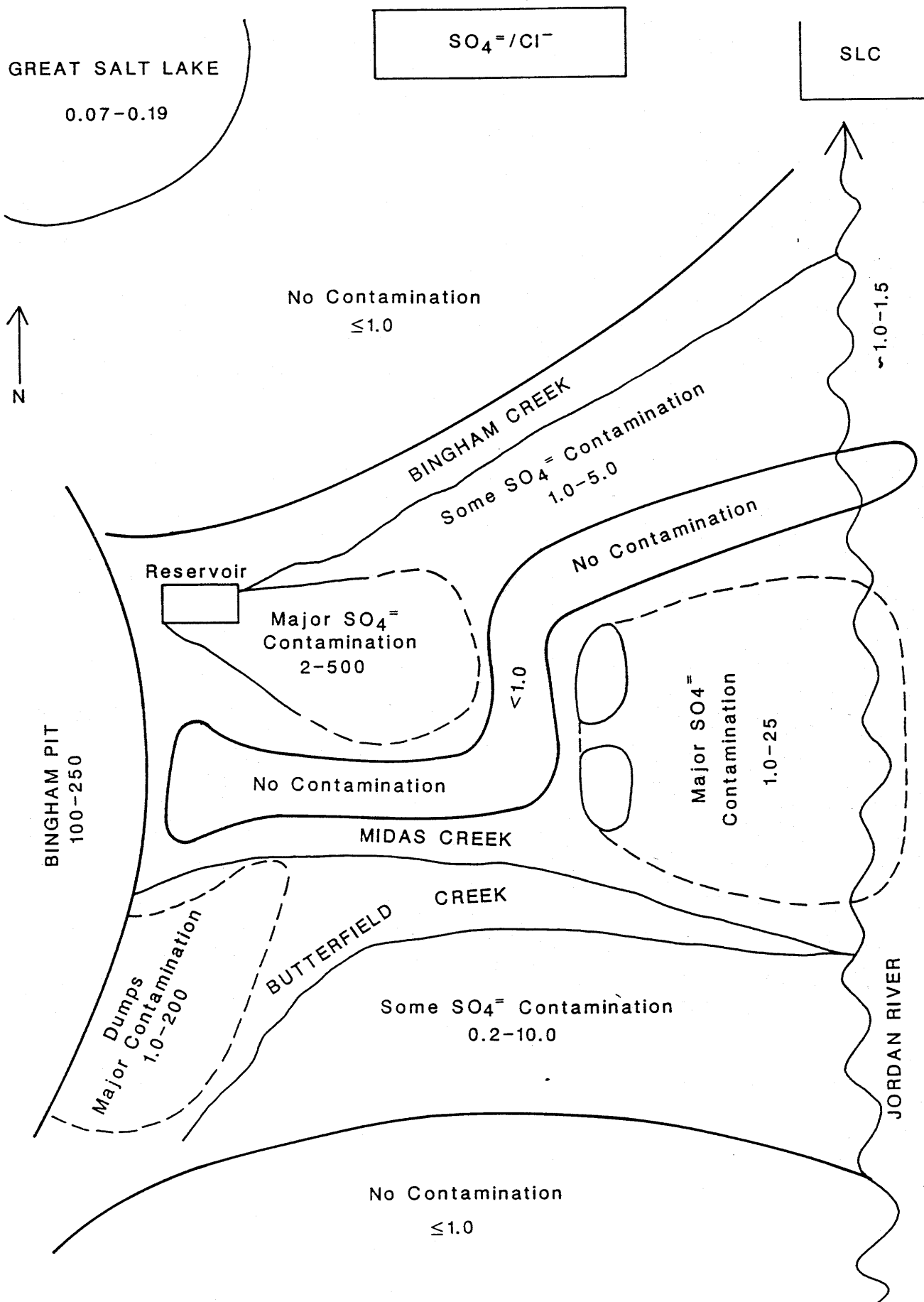


Figure I-5. SO_4 To Cl Ratio

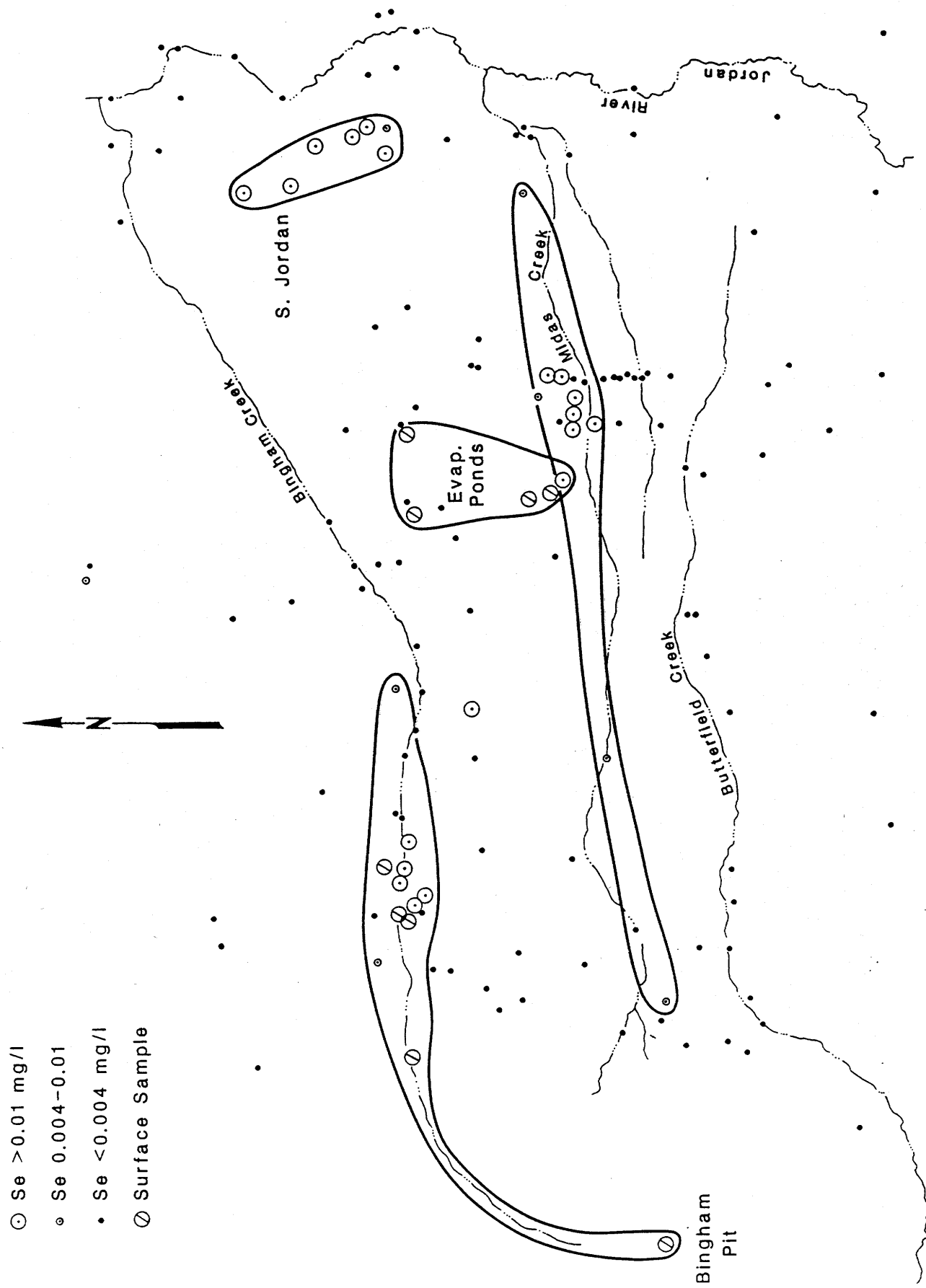


Figure I-6. Se Concentrations

GEOCHEMICAL X-SECTION

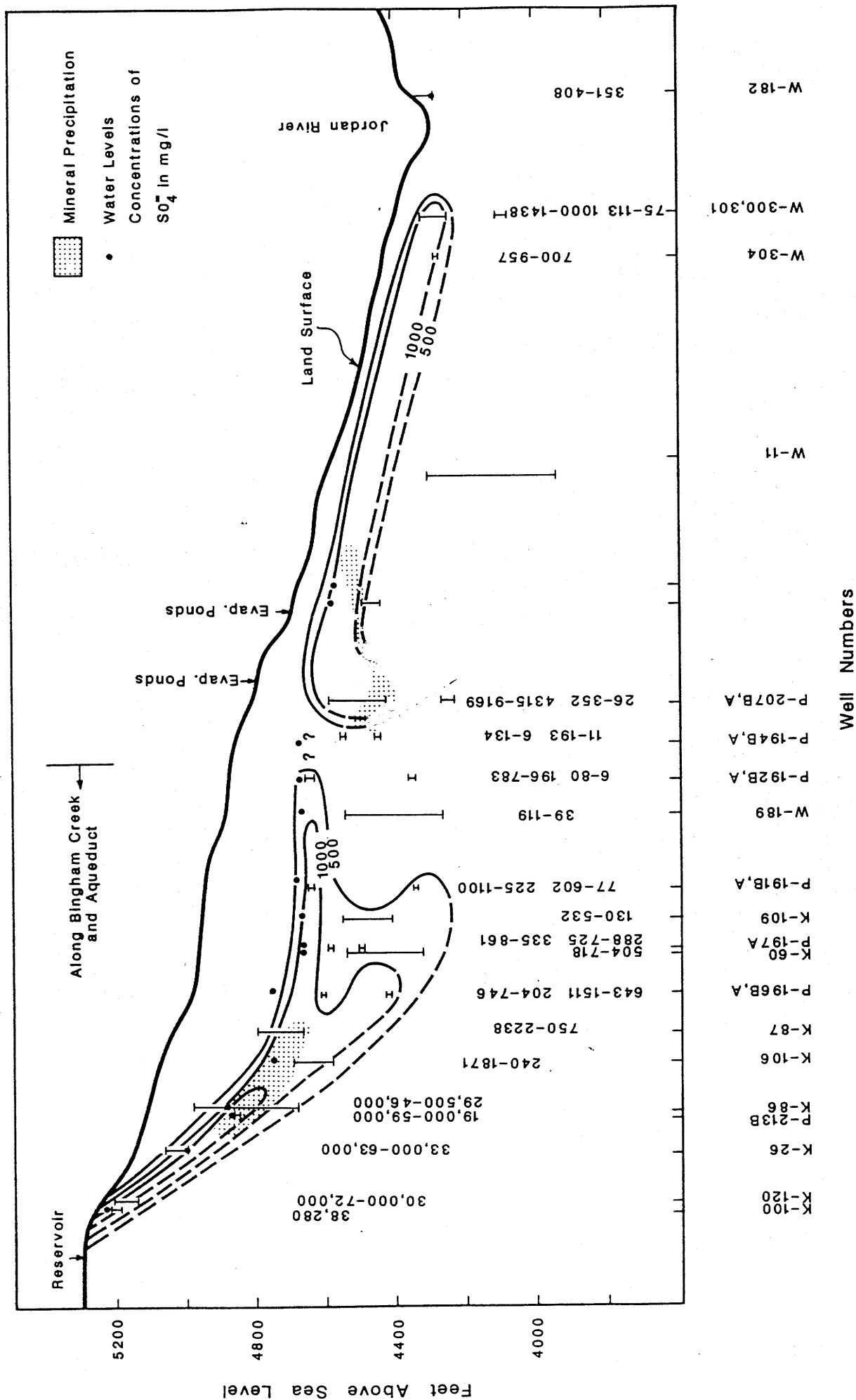


Figure I-7.

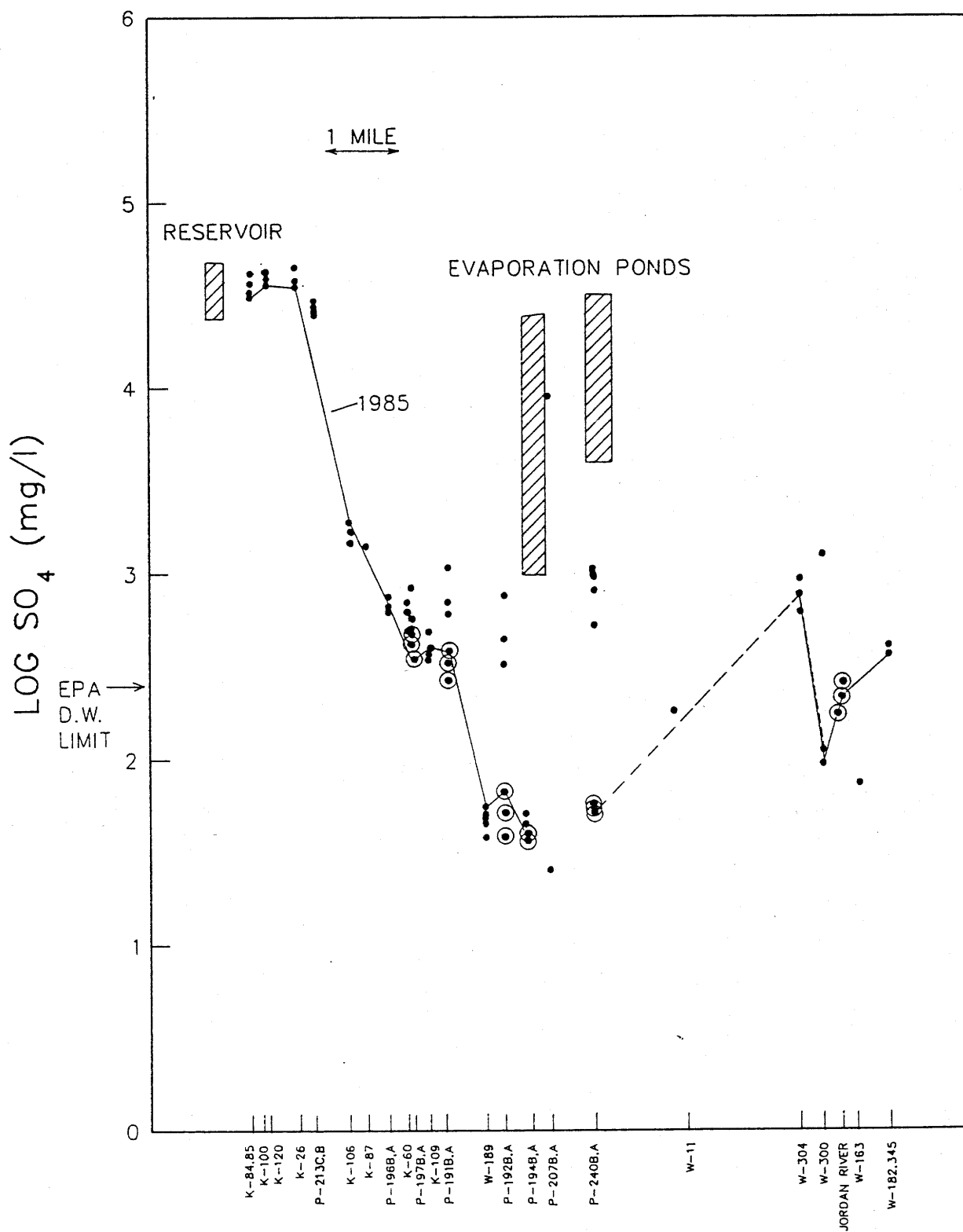


Figure I-8. Log SO₄ Concentrations
From Reservoir To Jordan River

TABLE I-1.

CHEMICAL COMPOSITION OF SNOW IN UTAH IN 1959

Constituent	Concentration, in mg/l	Number of Analyses
Calcium (Ca)	2.23	7
Magnesium (Mg)	.33	6
Sodium (Na)	.60	18
Potassium (K)	.47	6
Bicarbonate (HCO_3)	6.29	7
Sulfate (SO_4)	2.25	6
Chloride (Cl)	.97	18
Dissolved Solids (calculated)	10.58	6
$\text{SO}_4^{=}/\text{Cl}^{-}$	2.32	

Ref: Feth et al., 1964.

TABLE I-2.

SPRING WATER COMPOSITION¹

	Crystal Spring S-316 ²	Maple Spring S-319 ²	Barney's Spring S-318 ²	F-1 ³
SiO ₂	6	15	45	25
Ca	85	85	204	220
Mg	n.d. ⁴	n.d. ⁴	n.d. ⁴	73
Fe	0.12	--	0.07	n.d.
Na	6	38	245	2800
K	1	2	9	14
As	--	--	0.012	n.r.
SO ₄ ⁼	19	77	263	102
Cl ⁻	6	43	502	5025
HCO ₃ ⁻	225	345	390	362
F ⁻	0.22	0.23	0.30	n.r.
pH	7.4	8.7	7.3	n.r.
Temp.	11.0	11.0	12.0	n.r.
TDS	240	485	1653	n.r.
SO ₄ ⁼ /Cl ⁻	3.2	1.8	0.5	0.02
Elevation	7700'	6000'	5800'	n.r.

1) In mg/l

2) From Kennecott reports. Oquirrh Mountains.

3) From Spencer (1983). Wasatch Mountains.

4) n.r. = not reported

n.d. = not determined

-- = below detection limit

TABLE I-3.

HIGH CHLORIDE WATER COMPOSITIONS¹

	W-340 ²	W-336 ²	
SiO ₂	62	26	(0.5) ³
Ca	138	300	(1.0)
Mg	n.d. ⁴	n.d. ⁴	(1.0)
Fe	0.01	0.03	(0.01)
As	0.19	-- ⁴	(0.004)
Ba	0.60	0.90	(0.30)
Mn	0.44	0.03	(0.01)
Na	300	180	(1.0)
K	52	6	(1.0)
SO ₄ ⁼	83	90	(0.1)
Cl ⁻	611	895	(0.1)
HCO ₃ ⁻	290	165	(1.0)
F ⁻	2.5	0.31	(0.01)
pH	6.0	7.4	(0.02)
Temp(°C)	60	15	(0.5)
TDS	1470	1786	(3.0)
SO ₄ ⁼ /Cl ⁻	0.13	0.10	

- 1) In mg/l
- 2) From Kennecott reports
- 3) Estimated detection limit
- 4) n.d. = not determined
- = not detected

TABLE I-4.

W-31 WATER COMPOSITION REACTED WITH SULFIDES

	Original ¹ (mg/l)	After Reaction (mg/l)	Delta (mg/l)
SiO ₂	52	52	0
Ca	82	82	0
Mg	31	31	0
Fe	0.03	8.7	+8.7
Cu	0.02	0.4	-0.02
Pb	0.01 ²	0.001	-0.01
Zn	0.04	0.03	-0.01
Na	34	34	0
K	6.0	6.0	0
SO ₄	23	57	+34
Cl	157	157	0
HCO ₃	190	165	-25
F	0.2	0.2	0
O ₂ (aq)	10.0	0	-10.0
pH	7.1	6.8	0.3
Temp.	14.0	14.0	0
pE	4.0	-2.2	-6.2

AMOUNTS OF EACH MINERAL DISSOLVED

Pyrite (FeS₂) 15.5 mg/kg H₂O

AMOUNTS OF MINERALS PRECIPITATED

Chalcopyrite (CuFeS ₂)	0.6 x 10 ⁻¹	mg/kg H ₂ O
Galena (PbS)	0.2 x 10 ⁻¹	mg/kg H ₂ O
Goethite (FeOOH)	2.5	mg/kg H ₂ O
Sphalerite (ZnS)	0.2 x 10 ⁻¹	mg/kg H ₂ O

- 1) From Kennecott Annual Reports
- 2) Detection Limit Value.

TABLE I-5A.

REACTION OF K-26 WATER^a WITH AQUIFER MATERIALS

	Initial	Final	P-197A
Ag	0.07	0.04	0.01 ^c
Al	3710	0.03	0.1 ^c
As	1.24	1.24	0.004 ^c
Ca	75	1210	260
Cd	0.39	0.024	0.01 ^c
Cu	161	0.2×10^{-5}	0.01 ^c
Fe	1186	0.4×10^{-7}	0.03 ^c
K	1	1	5
Mg	5000 ^b	710	76
Mn	324	21	0.01 ^c
Na	29	29	89
Ni	29.1	29.1	0.13
Pb	0.9	0.4	0.07
Zn	208	0.04	0.03
SiO ₂	118	27	20
SO ₄	38455	827	515
Cl	187	187	219
HCO ₃	1	91.5	194
pH	3.1	7.1	7.1
pE	?	8.0	?
T(°C)	19	19	13
P _{CO₂}	?	$10^{-2.5}$?

a) In mg/l

b) Estimated

c) Detection Limit Values

TABLE I-5B.

QUANTITIES OF MATERIALS REMOVED FROM OR ADDED TO SOLUTION

REMOVED:

	mg/kg H ₂ O
CaSO ₄ ·2H ₂ O (Gypsum)	64725
Al ₄ OH ₁₀ SO ₄	13525
CaMg(CO ₃) ₂ (Dolomite)	10750
CO ₂ (gas)	9823
FeOOH (Goethite)	1750
MnCO ₃ (Rhodochrosite)	669
ZnSiO ₃	474
CuFeO ₂	403
PbCO ₃ (Cerrusite)	0.7
CdCO ₃ (Otavite)	0.6
AgCl (Cerargyrite)	0.04

ADDED:

CaCO ₃ (Calcite)	59190
SiO ₂ (Quartz)	139

TABLE I-6A.

SULFIDE PRECIPITATION

	Initial ^a	Final ^a	P-197A ^a
Ag	0.04	0.7×10^{-9}	0.01^b
Al	0.03	0.03	0.1^b
As	1.24	1.24	0.004^b
Ca	1210	1210	260
Cd	0.024	0.005	0.01^b
Cu	0.2×10^{-5}	0.5×10^{-8}	0.01^b
Fe	0.4×10^{-7}	0.4×10^{-7}	0.03^b
K	1	1	5
Mg	710	710	76
Mn	21	21	0.01^b
Na	29	29	89
Ni	29.1	29.1	0.13
Pb	0.4	0.01	0.07
Zn	0.04	0.04	0.03
SiO ₂	27	23.2	20
SO ₄	827	862	515
Cl	187	187	219
HCO ₃	91.5	65.2	194
pH	7.1	6.9	7.1
pE	4.0	-2.0	?
T(°C)	19.0	19.0	13
P _{CO₂} (atm)	$10^{-2.5}$?

a) In mg/l

b) Detection Limit Values

TABLE I-6B.

QUANTITIES OF SULFIDES PRECIPITATED FROM SOLUTION

REMOVED:		mg/kg H ₂ O
Greenockite	(CdS)	0.3
Chalcocite	(CuS)	0.3×10^{-5}
Galena	(PbS)	0.5
Silver Metal	(Ag)	0.04

TABLE I-7A.

REACTION OF BACKGROUND WATER WITH OXIDIZED MINERALS

	W-31 ^a (10-23-85)	Calculated	P-197B
Ag	0 ^b	0.037	0.01
Al	0 ^b	0.04	0.1
Ca	82	358	260
Cd	0 ^b	0.008	0.01
Cu	0 ^b	0.3×10^{-5}	0.01
Fe	0 ^b	0.2×10^{-7}	0.03
K	6	6 ^c	4
Mg	32	209	76
Mn	0 ^b	5.8	0.01
Na	34	34 ^c	89
Pb	0 ^b	0.3	0.07
SiO ₂	52	22	20
Zn	0 ^b	0.008	0.03
Cl	157	157 ^c	219
HCO ₃	190	97	194
SO ₄	23	1468	448
F	0.22	0.22 ^c	0.22
pH	7.1	7.4	7.1
Pe	?	8.0	?
T(°C)	14	14.0	13.0
P _{CO₂} (atm)	?	$10^{-2.5}$?

a) In mg/l

b) Below detection limit. Assumed to be zero.

c) No change because not included in mineral phases.

TABLE I-7B.

QUANTITIES OF MATERIAL REMOVED FROM OR ADDED TO SOLUTION

REMOVED:

mg/kg H₂O

CaCO ₃ (Calcite)	1547
CO ₂ (gas)	51
SiO ₂ (Quartz)	30
FeOOH (Goethite)	0.05

ADDED:

CaSO ₄ ·2H ₂ O (Gypsum)	2591
CaMg(CO ₃) (Dolomite)	1345
MnCO ₃ (Rhodochrosite)	12.2
PbCO ₃ (Cerrusite)	0.2
Al ₄ (OH) ₁₀ ·SO ₄	0.14
AgCl (Cerargyrite)	0.05
ZnSiO ₃	0.02
CdCO ₃ (Otavite)	0.01
CuFeO ₂	0.7 x 10 ⁻⁵

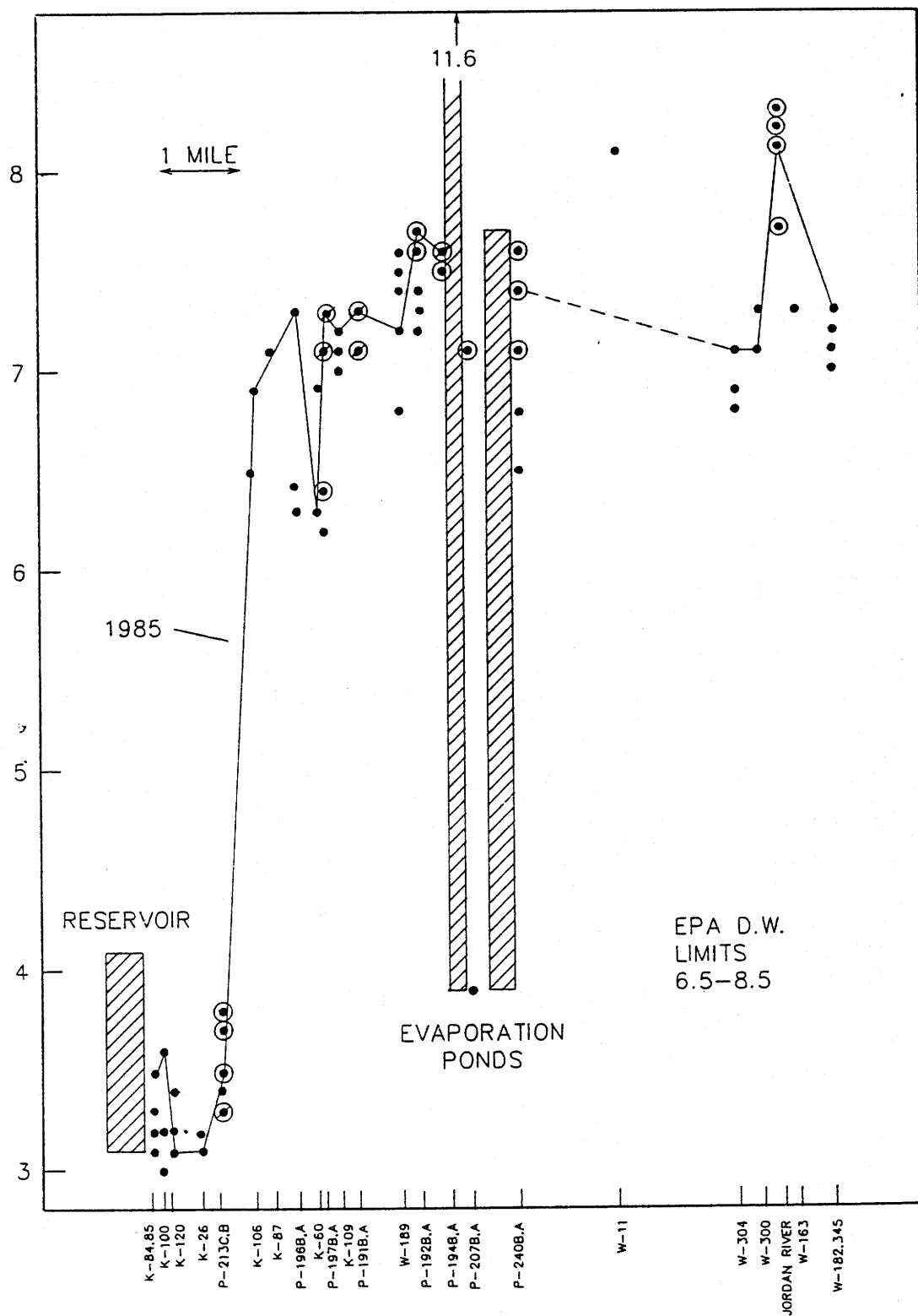
APPENDIX I-A.

The Figures in this appendix are plots of data for groundwaters from wells along the transect from the reservoirs to the Jordan River. Data for the years 1983 to 1985 are plotted. Data points for the year 1985 are connected with a line. Ranges of observed concentrations are plotted for the reservoirs and evaporation ponds.

Symbols are as follows:

- well with single perforated zone;
- ⊙ Lower perforation in well with 2 perforated zones;
- ⊙ Data point where upper and lower zones have same concentration;
- D.L. Detection Limit;
- E.P.A. D.W. Environmental Protection Agency Drinking Water Concentration Limit

pH



LOG Al (mg/l)

D.L. → -1

4

3

2

1

0

-1

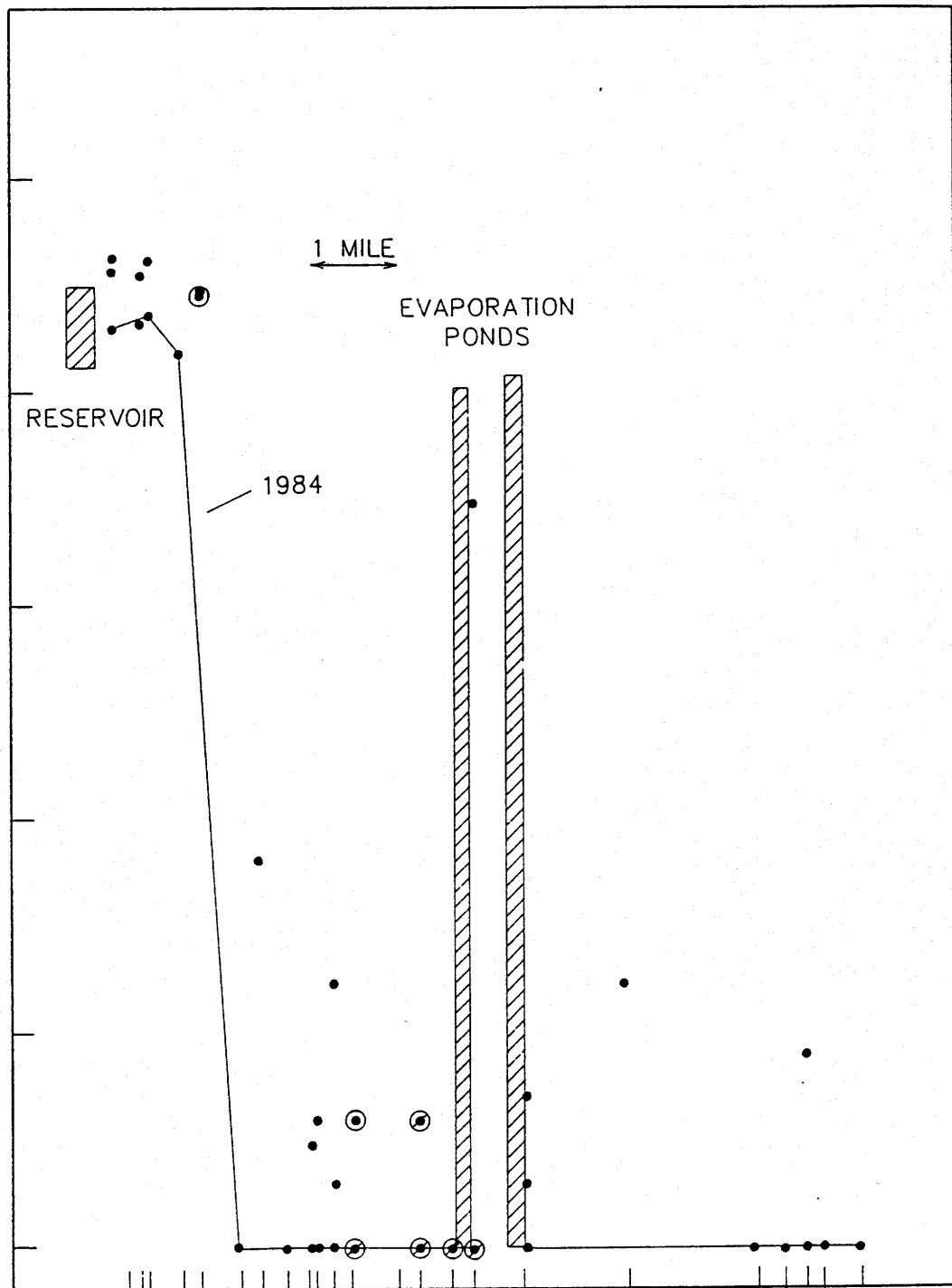
1 MILE

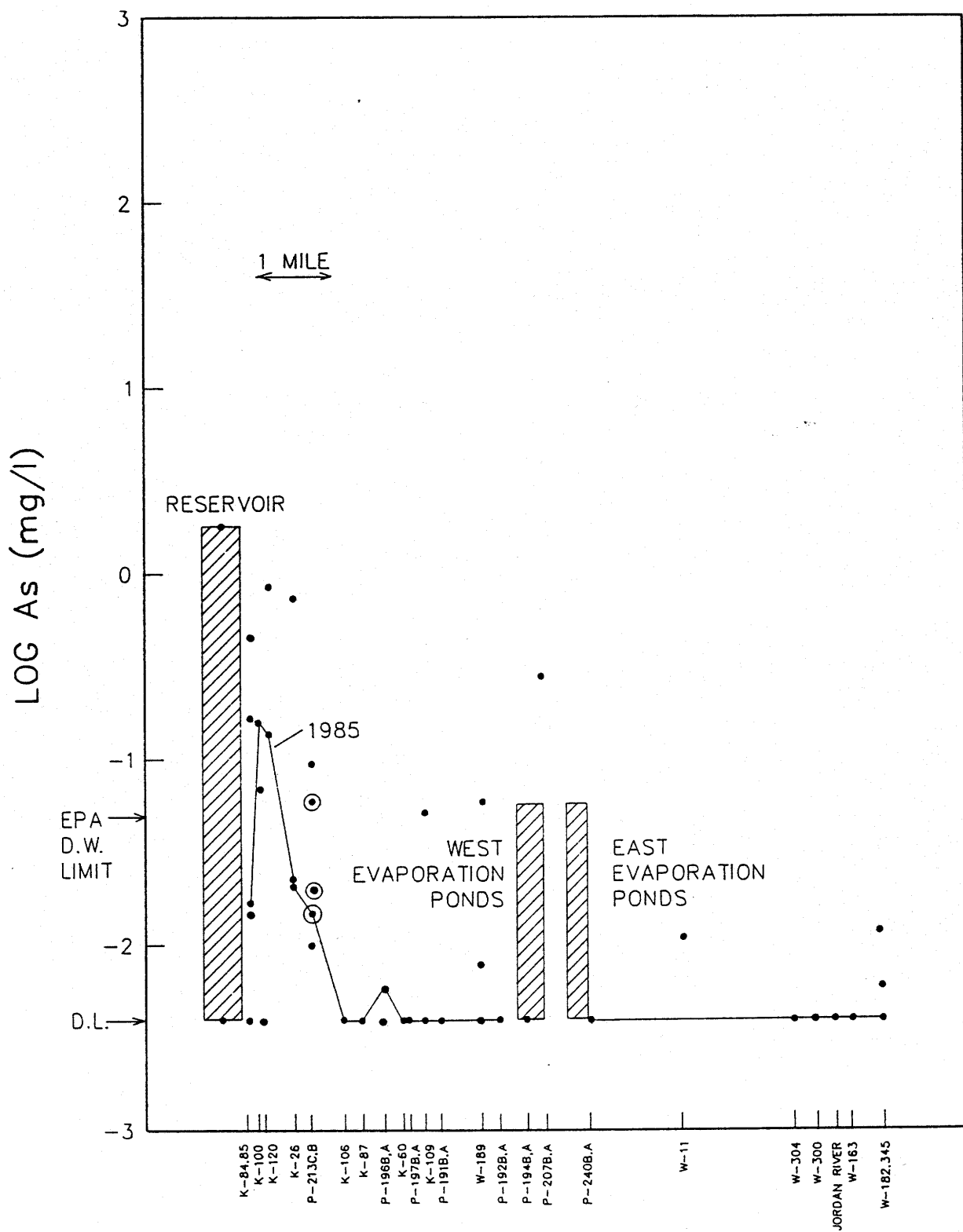
EVAPORATION
PONDS

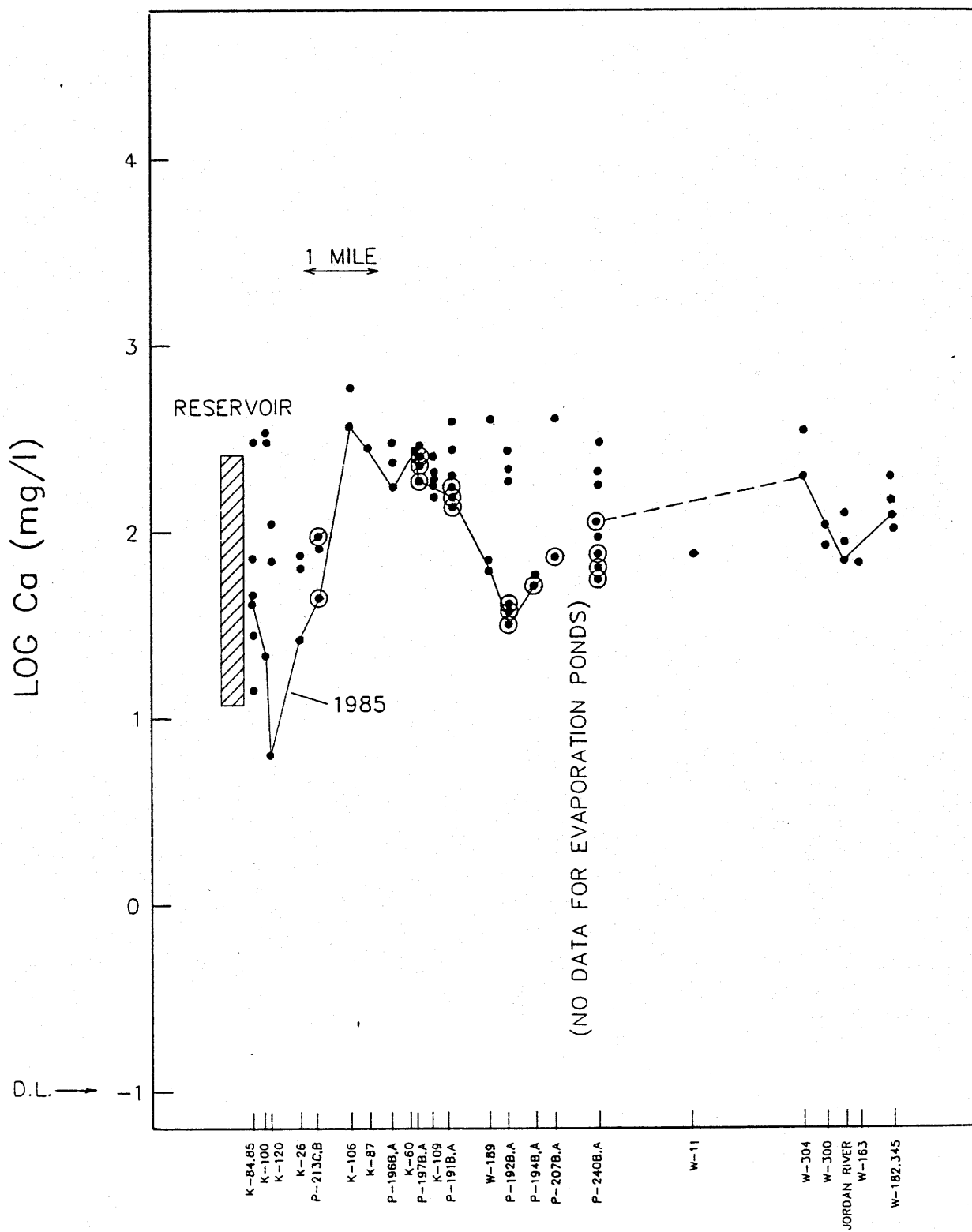
RESERVOIR

1984

K-84.85
K-100
K-120
K-26
P-213C.B
K-106
K-87
P-196B.A
K-60
P-197B.A
K-109
P-191B.A
W-189
P-192B.A
P-194B.A
P-207B.A
P-240B.A
W-11
W-304
W-300
JORDAN RIVER
W-163
W-182.345

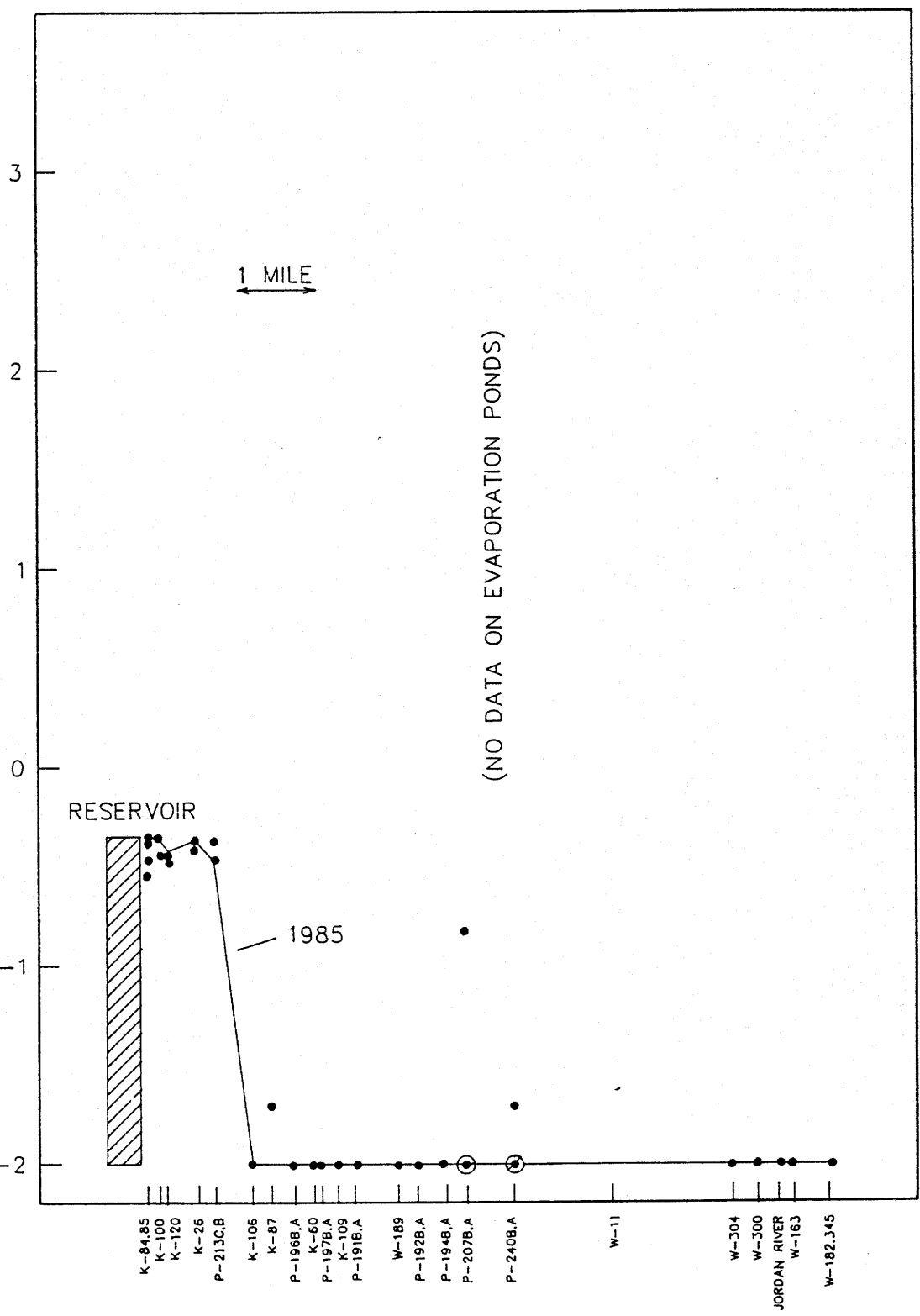


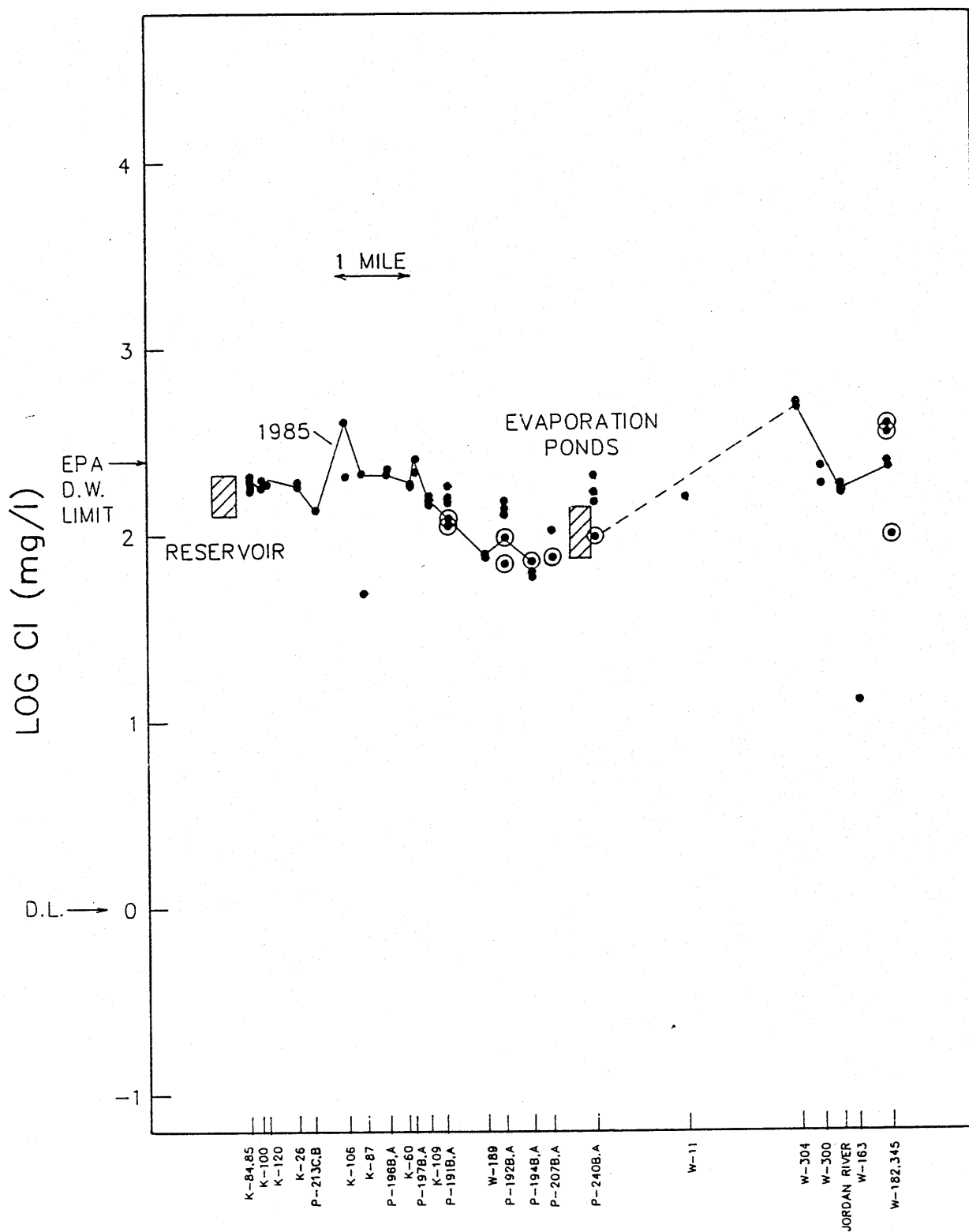




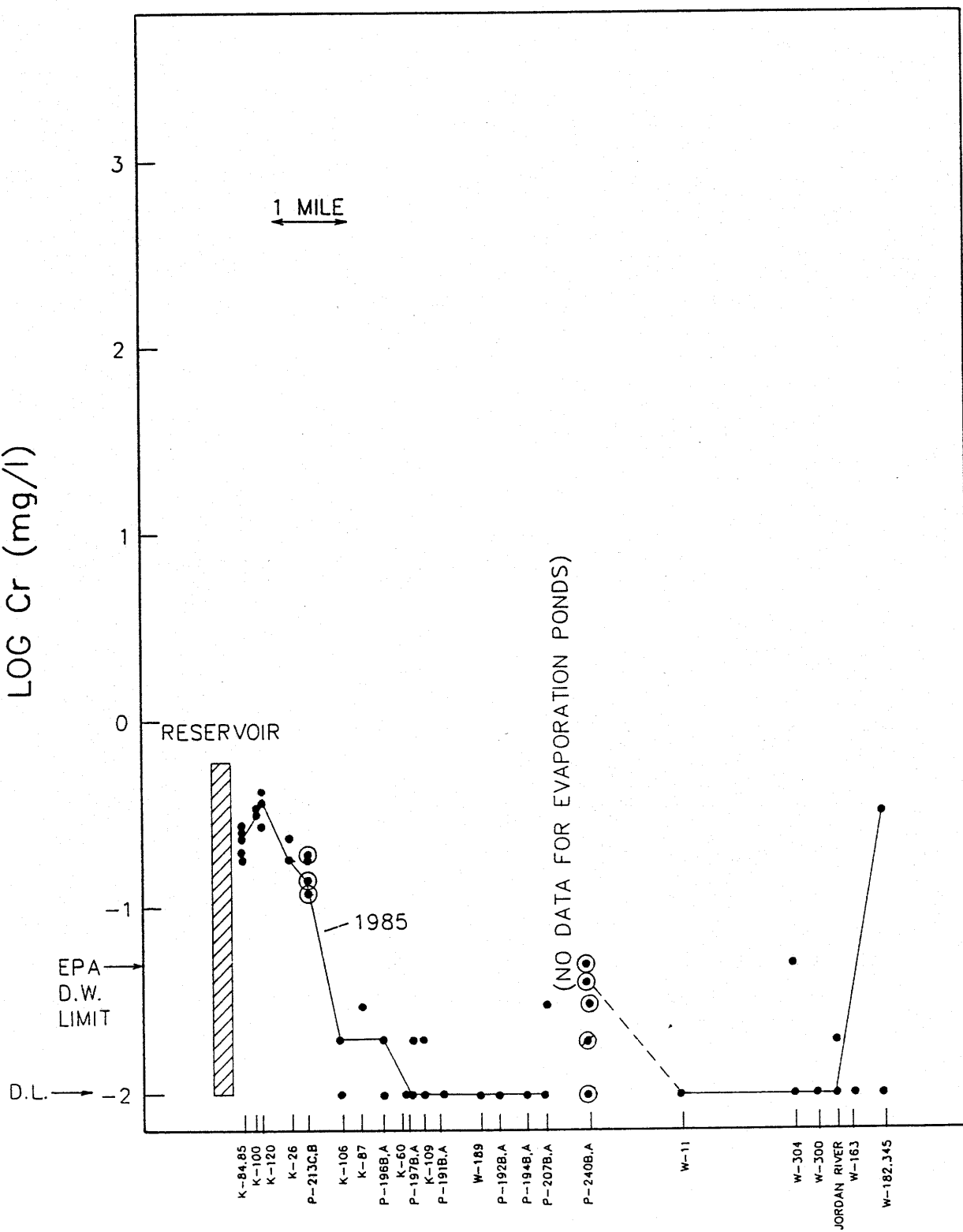
LOG Cd (mg/l)

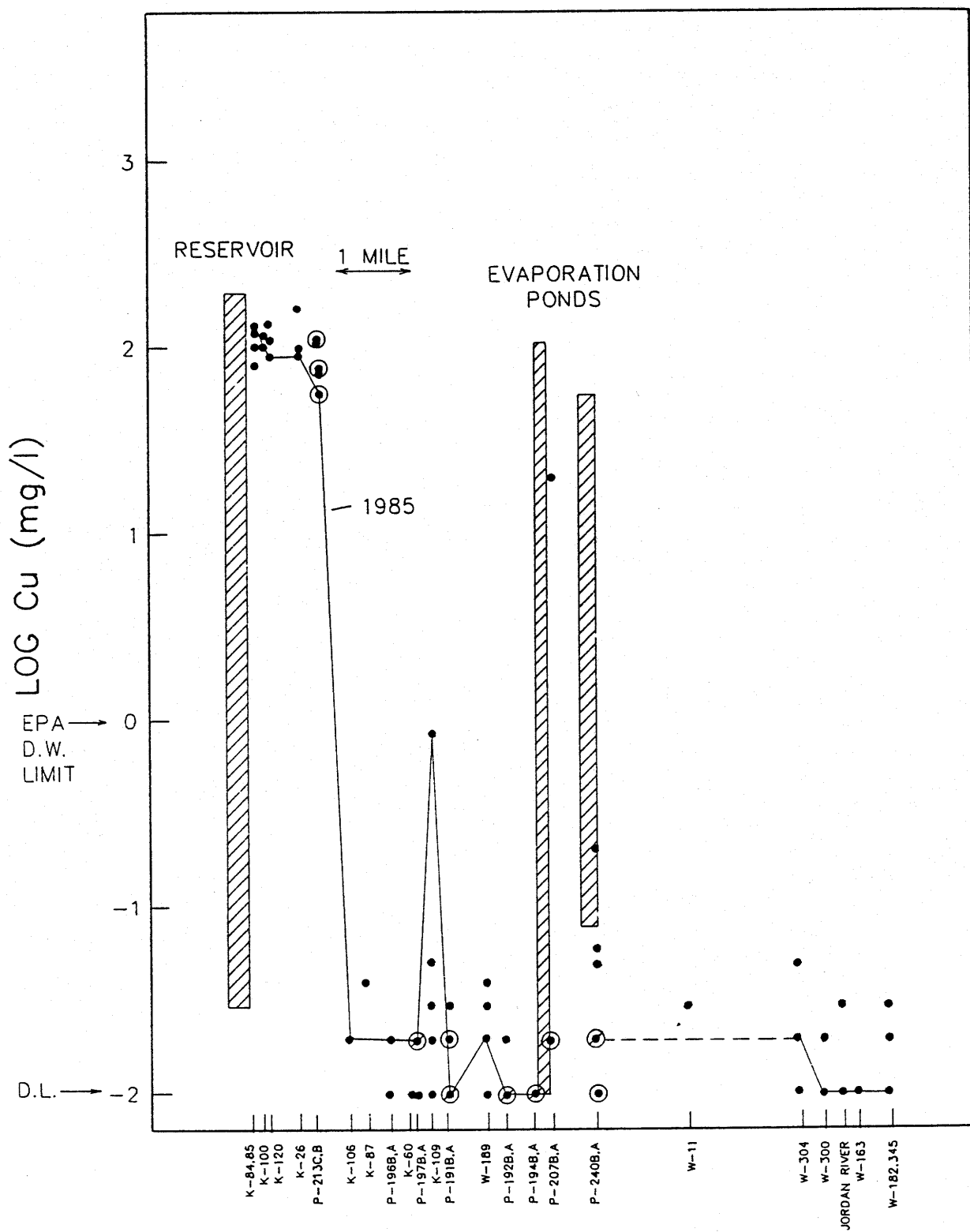
D.L. & EPA D.W. LIMIT



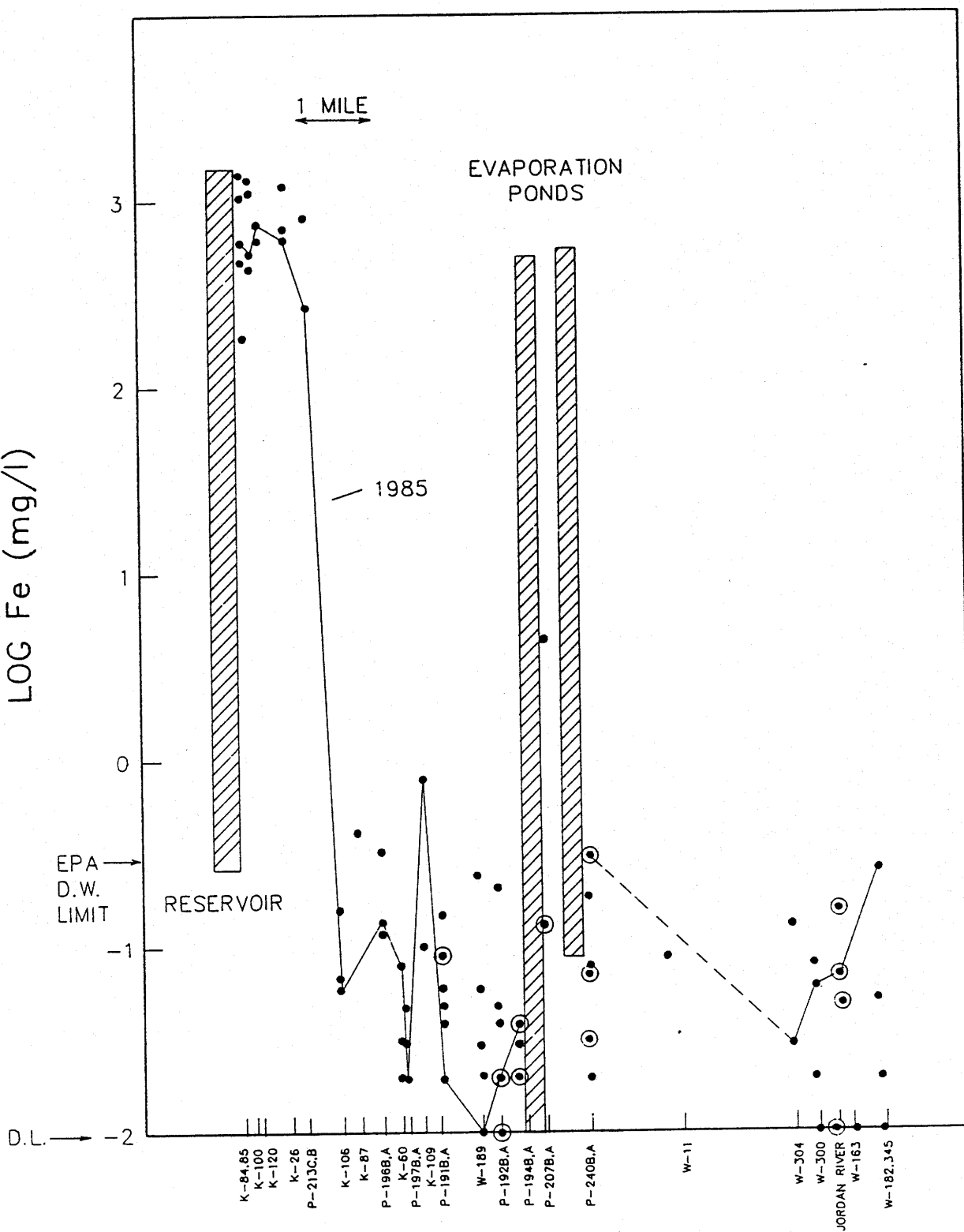


LOG Cr (mg/l)

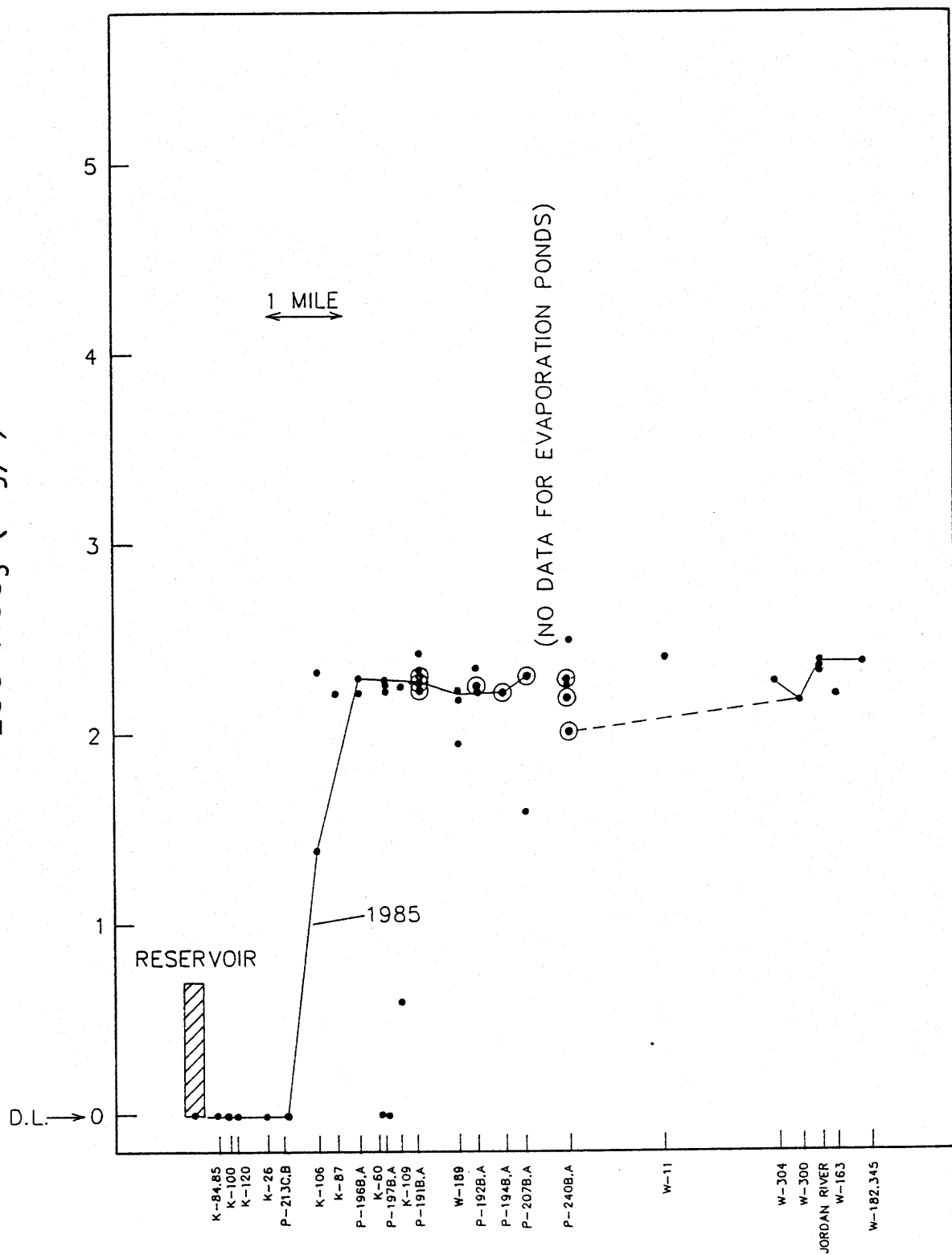


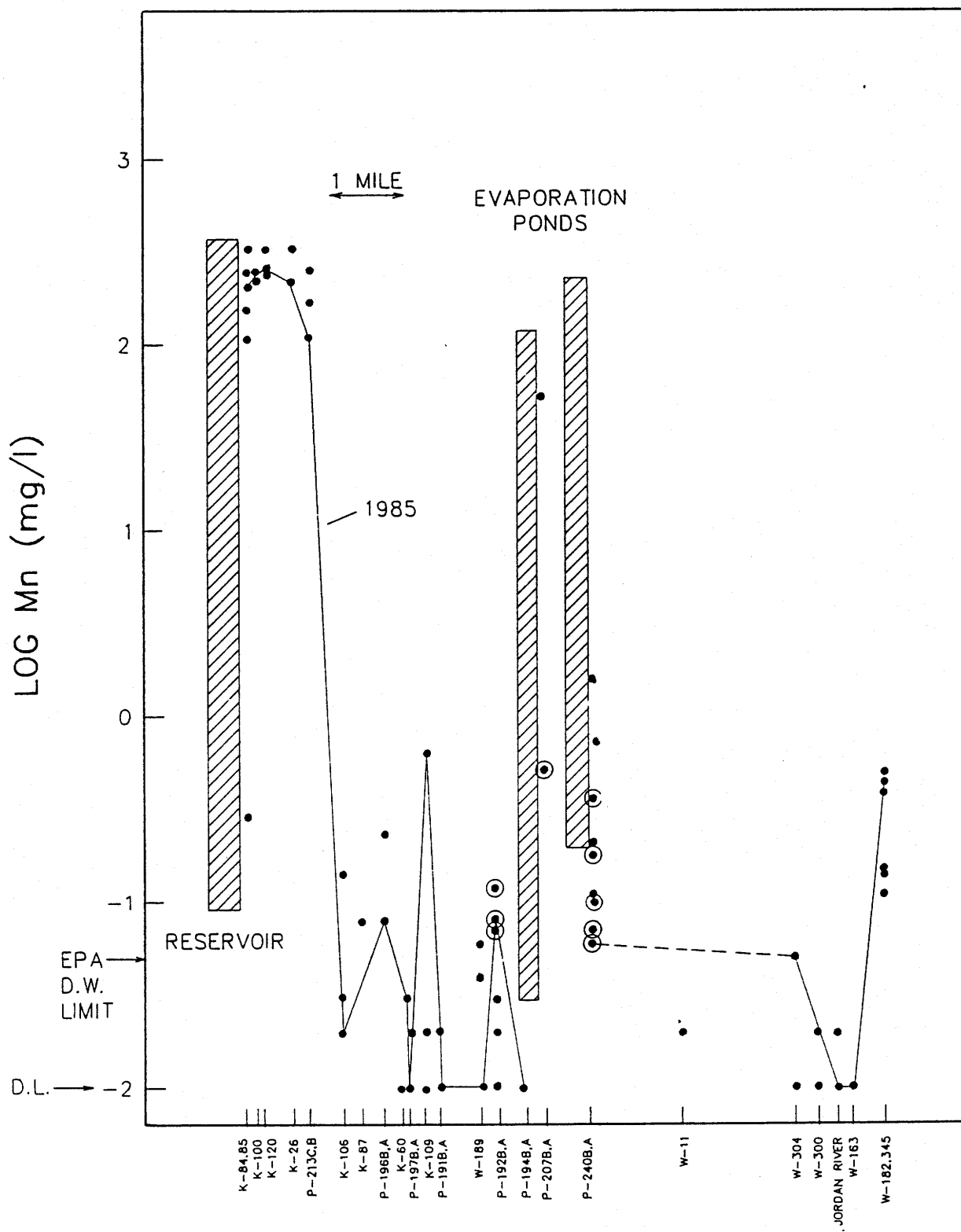


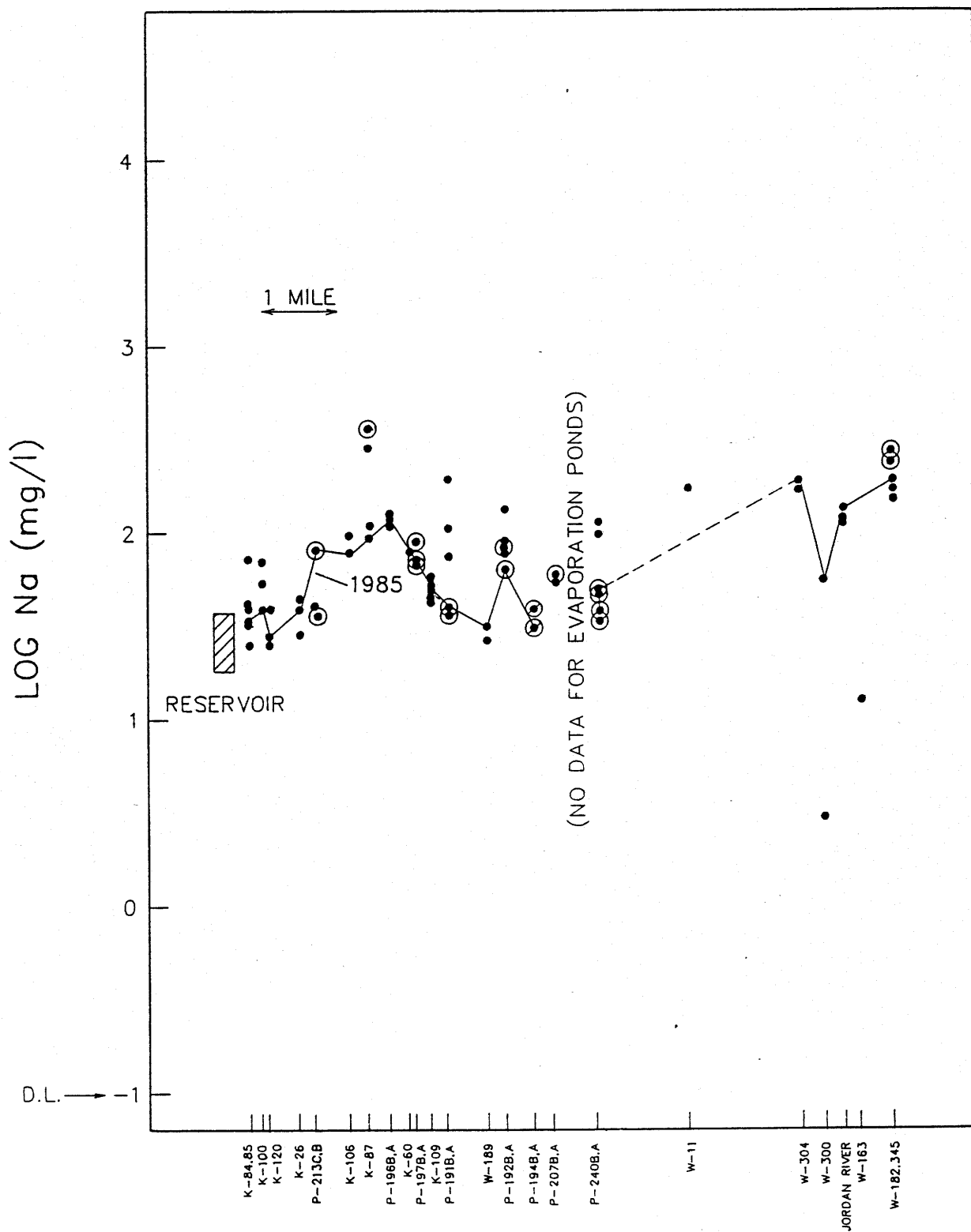
LOG Fe (mg/l)

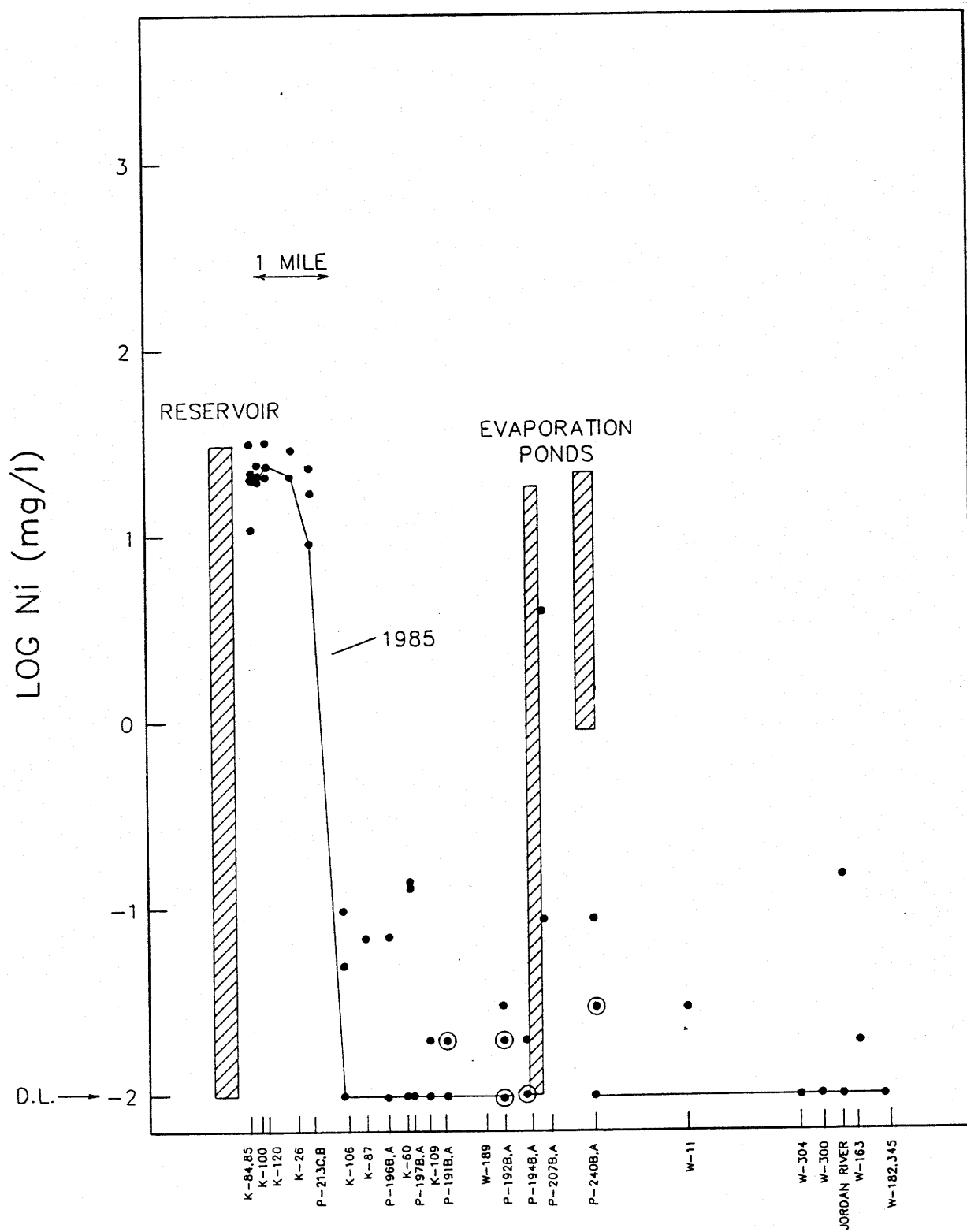


LOG HCO_3 (mg/l)

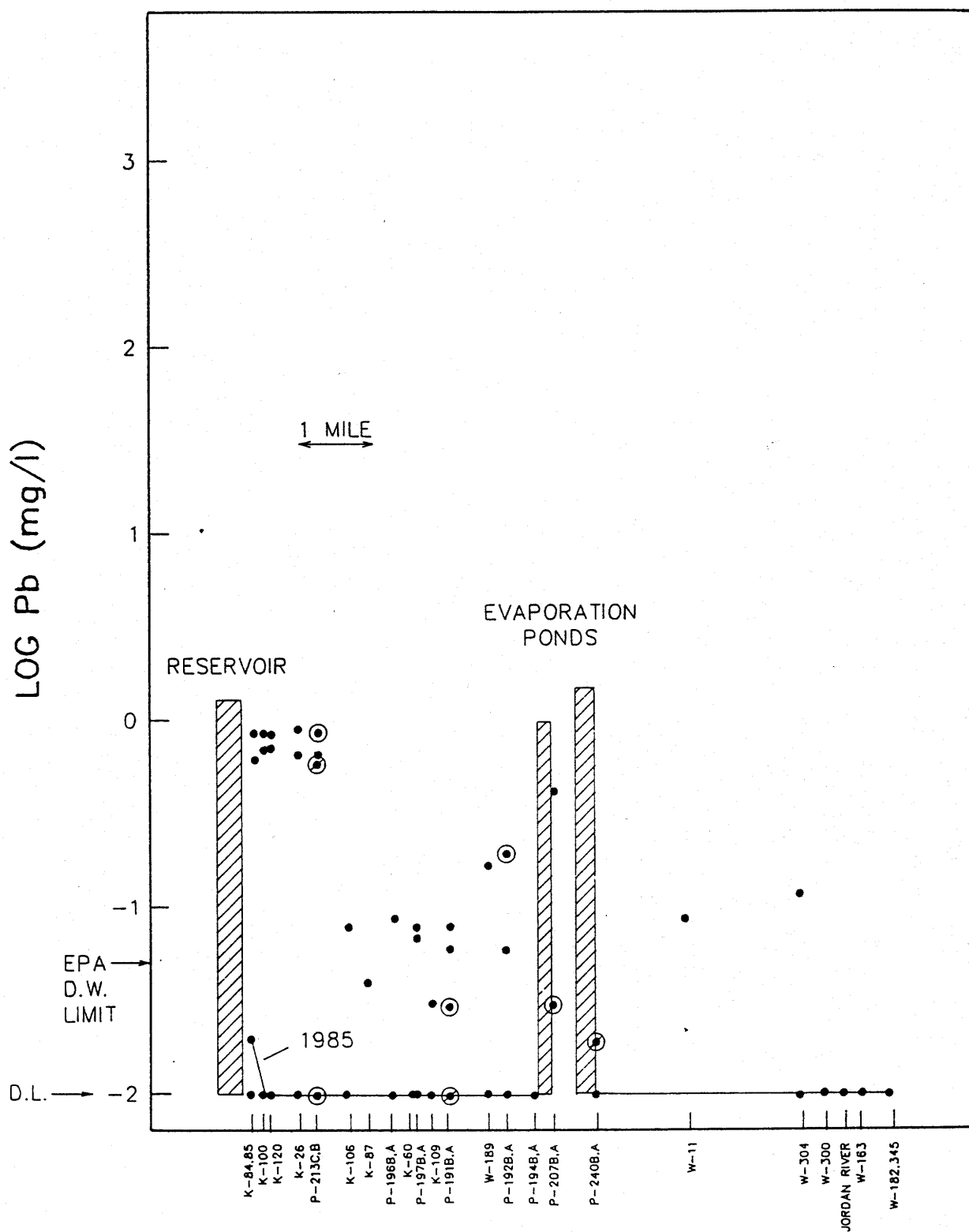


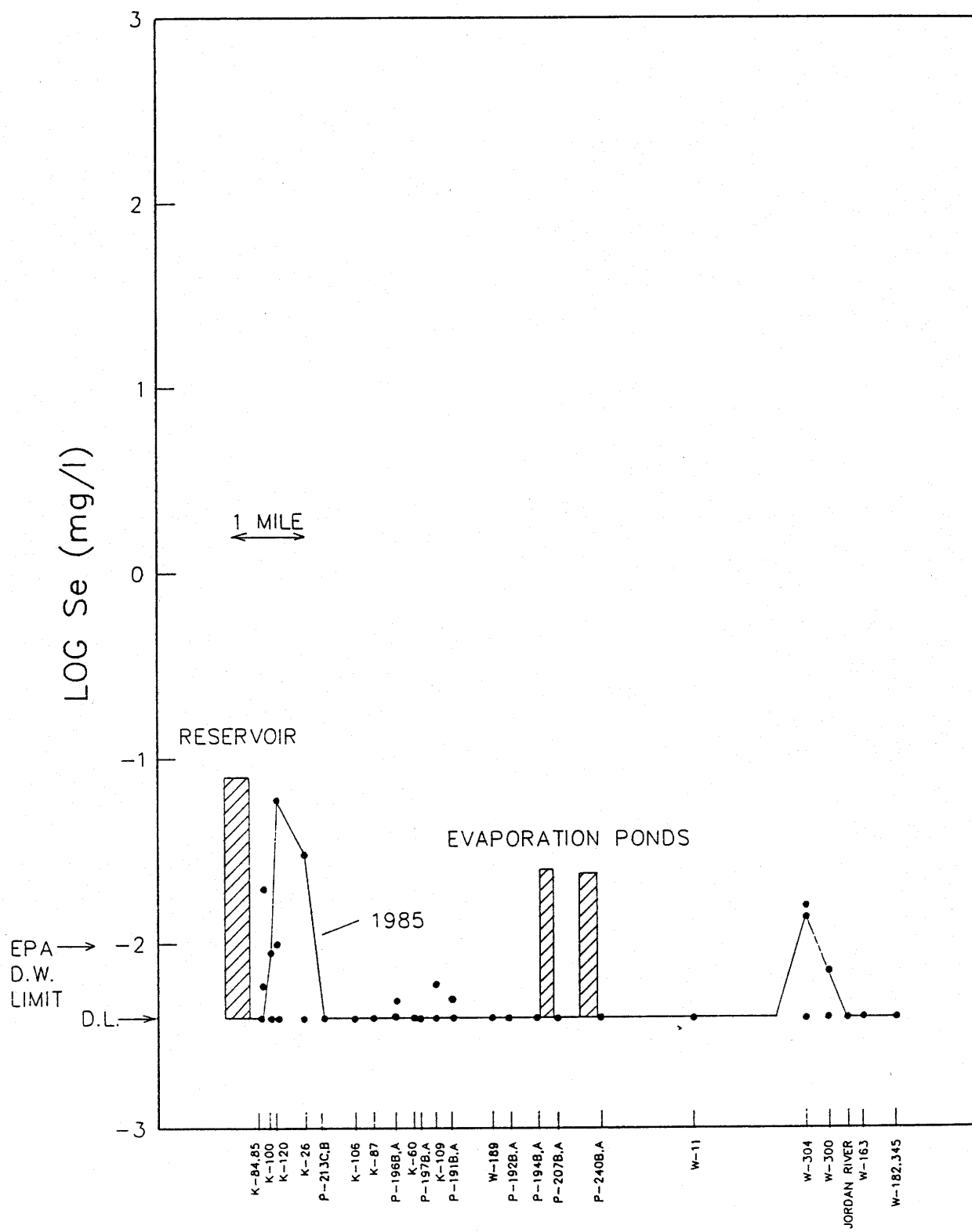






LOG Pb (mg/l)





LOG SiO₂ (mg/l)

D.L. → 0

